PARTICLE SIZE SPECTRUM AND COMPRESSIBILITY OF RAW AND SHREDDED MUNICIPAL SOLID WASTE

By

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To my parents

and

wife

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The particle size spectrum and density-compressibility of raw and shredded municipal solid waste were investigated. The particle size spectrum was determined using large soil-aggregate sieves and large size samples. The dried samples varied in size from 2.17 to 16.55 lbs. Four different types of waste were analyzed: raw refuse and three different types of shredded waste. A total of 63 test samples were sieved. The sieve fractions of each test sample were separated into their component parts, e.g., paper, glass, plastic, etc. Particle size distributions were obtained for the composite wastes and their constituents.

The density and compressibility of "twin samples" of the particle size analysis were determined using a 12.094 in. ID x 10.969 in. test cylinder. Some 79 test samples were analyzed by the combined density-compression test. The average sample size was 3.23 lbs. The raw and shredded waste materials were gently placed into the cylinder and the loose bulk density

determined for each test. The samples were statically loaded using a hand-pumped hydraulic cylinder with large steel piston. Increased pressures from 0 to 174.7 psi were incrementally applied to the test samples and the corresponding densities measured. The total loading time averaged 29.3 minutes. Three rebound measurements were made during the analysis.

The particle size and the combined density-compression analytical techniques were found to be dependable and reproducible. The major variation resulted from the different compositions of test samples.

Particle size distributions were obtained for the refuse components. Mathematical functions were fitted to each distribution and methodologies were developed for predicting particle size distributions of different raw and processed composite wastes. Hammermills tended to reduce the waste to log-normal type distributions while rasp shredders tended to produce beta distributions. Hammermill shredders increased the coefficient of variation, while it was slightly reduced by the rasp.

The mean particle size of shredded waste was found to be directly proportional to the size of the shredder grate, as measured by the minimum width of the largest grate opening.

Each waste component reacted differently to shredding and to the different types of shredders. Glass was the easiest to reduce by the hammermills, while textiles, plastic and metals were difficult to break down. The rasp produced considerably coarser glass than the hammermills.

The dry bulk density from the compression curves was found to vary with the logarithm of applied pressures. The waste particle size distribution (as defined by the product of the mean and standard deviation) and the waste composition also were important variables. Mathematical functions were fitted to the data. The models were very accurate in predicting the data obtained from the study and those reported by others. The equations were modified to account for moisture content.

CHAPTER I

INTRODUCTION

Objectives of Investigation

Mixed refuse or solid waste is a heterogeneous mass of particles of different materials, e.g., paper, glass, plastic, metal, etc., of different sizes, configurations, rigidity, densities, and other characteristics. Its composition varies considerably depending on where it is collected (residence, stores, etc.), the season of the year, the day of the week, the size and type of community, and the geographic location. Its physical and chemical characteristics are directly affected by the various materials or components of the mixture.

Individual particles of raw refuse are almost always irregular and may range from small items, such as soil, sand, and grass, to bulky items, such as discarded furniture and appliances. The configuration of the particles may vary from long cylinders (e.g., tree branches), thin sheets (e.g., paper, plastics, fabrics), short cylinders (e.g., cans and bottles), spheroids (e.g., sand, rock, and food), large rectangular items (e.g., boxes and cartons), to small jagged particles. Because of its many components, the individual particles of municipal refuse can be large or small, organic or inorganic, hard or soft, flexible or brittle, fragile or tough, smooth or rough, dry or wet, dense or light, or fibrous.

One of the most important physical characteristics of solid waste is the size of its individual particles. The spectra of particle sizes of raw and shredded waste uniquely characterize the components of refuse and the performance of any processing machinery, e.g., shredders. The particle sizes of municipal refuse also have an important role in the efficiency of many solid waste systems, such as milled landfills, pyrolysis, suspension furnaces, composting, pipeline transportation, air classifiers, and other solid waste separation and bio-chemical processes. The need to measure particle sizes of solid waste in order to optimize the efficiency of these systems is obvious.

Unfortunately, although analytical techniques have been developed to evaluate and measure various chemical, physical, and microbiological characteristics of air, water, and waste water, researchers have not yet successfully applied these same efforts to define and characterize solid waste. The literature review revealed that knowledge of the physical and chemical composition of refuse is surprisingly meager. At a time when the field of analytical chemistry is directed toward methods and equipment of micro-samples and micro-sensitivities, we are faced with the need to physically analyze large-sized samples in order to arrive at reliable characterizations of solid waste.

Most of the analytical procedures presently used to determine chemical characteristics of municipal solid waste were not developed for solid waste, but for the agricultural and mineral industries, and the air, water, and waste water sectors. Almost all of these methods generally use a very small, relatively homogeneous sample with small particle sizes, unlike the very large particles and heterogeneous material found in municipal waste. Subsequently, these methods required modification when applied to solid waste [1].

Although no reliable quantitative method has been sufficiently developed yet for measuring particle sizes of raw and shredded solid waste, various attempts have been made using screens, hand-sorting, and visual judgment. Only marginal information is available regarding the efficiency and success of these methods. Various researchers have mentioned specific refuse particle sizes but have not described their techniques. It has also been common to report particle sizes from shredders by the size of the shredder grates.

Since the density of raw and shredded refuse is one of the critical factors affecting its transportation, processing, and disposal, an effort also must be made to correlate particle size distributions with density. Only marginal information is available on changes in refuse density caused by shredding. It also appears that the compressibility[1] of shredded waste varies with respect to refuse particle size.

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[1] The "compressibility" of a material can be defined as the volume decrease due to a unit load.

The objectives of this research are listed below:

(1) to develop standard laboratory techniques for determining (a) particle size, (b) density, and (c) compressibility, specifically for raw and shredded municipal refuse;

(2) to determine the particle size distributions, densities, and compressibility of raw municipal refuse, and of primary and secondary shredded refuse from the Gainesville, Florida, compost plant;

(3) to determine the particle size distributions for the various refuse components (e.g., paper, plastic, metal) of the above composite wastes and define the particle size relationships between the components and the composite;

(4) to determine the particle size distributions, densities, and compressibility of shredded refuse from the Johnson City, Tennessee, compost plant;

(5) to determine the particle size distributions for the various refuse components of the above composite wastes and define the relationships between the components and the composite;

(6) to determine the relationships between refuse particle size, density, and compressibility;

(7) to determine the characteristics of each respective particle size distribution, how to express the distributions, and how the distributions are affected by additional shredding;

(8) to develop a technique for predicting particle size distributions for various raw municipal refuse, knowing only

the proportion of components; and

(9) to develop a technique of predicting particle size distributions for various processed wastes, knowing the processing technique and the proportion of components.

Rationale of the Approach

The first step in this research effort was to review the literature to determine the appropriate methods for (1) sampling, (2) sample preparation, (3) particle size analysis, (4) component classification, and (5) density and compressibility analysis for municipal solid waste. The literature was also reviewed to determine appropriate methods for expressing the data and defining the relationships among the various parameters.

In deciding which analytical techniques to use, an analyst must first consider the purpose of the analysis. For example, what is generally required in industrial processes for the particle spectrum of solid waste is not the size of the particles, but the value of some property of the particles that is size dependent, e.g., chemical reactivity. In such circumstances it is important, whenever possible, to measure the desired property, rather than measure the size of the particles by some other method and then deduce the required property. Also, the analytical techniques chosen must not destroy or alter certain characteristics of the samples which may be analyzed at a later time. Nevertheless, the final criterion for choosing an analytical technique is that it measure the appropriate property with accuracy and reproducibility sufficient for the particular application, yet still be reliable, simple, inexpensive, and timely [2].

The most promising analytical techniques discovered in the literature were chosen for further research and development. The preferred methods were those which appeared reasonably adaptable to municipal solid waste. The techniques found in the industrial, soil, and mineral sectors were usually not directly applicable because solid waste is considerably more heterogeneous and contains larger amounts of organics and larger sized particles than are commonly found in materials in other sectors. These considerations required development and modification of the techniques before they could be utilized. A significant portion of the total research was devoted to the development of analytical techniques suitable for use with municipal solid waste.

Several solid waste samples were analyzed using the proposed methods, with alterations made as necessary. The reliability of the methods were determined on multi-samples and evaluated in conjunction with particle size distributions, densities, and compressibilities for raw and shredded municipal refuse samples.

After the sensitivity and reliability of the analytical techniques were statistically evaluated and the analyses completed on various types of municipal and processed refuse, the best methods of expressing the data were determined and presented. The relationships between the components and the composite were evaluated and presented. A comparison was made of different types of samples. Statistical testing was used to determine if there was a difference between the samples. Simple and multiple regression techniques and the analysis of variance were used to determine the relationships among the various variables.

Previous observations and investigations indicated each component of raw municipal refuse had a distinct particle size distribution and that further processing would alter this distribution in a predictable manner. Thus, a method was proposed to determine the particle size distributions of raw and processed refuse, knowing only the mechanical process and the mixture of various components in the refuse.

CHAPTER II

SAMPLE COLLECTION AND PREPARATION

Introduction

Accurate sampling and sample preparation techniques are important and basic requirements for further analysis. The reliability of the analysis depends on the reliability of sampling and sample preparation techniques. Great care must be taken to obtain samples which are truly representative of the material to be tested, especially with regard to the parameters which will be measured. Numerous inconsistencies result from sampling which does not truly represent the material in question. Therefore, a standardized method should be adopted to increase both accuracy and reproducibility [2,3]. This is true not only for sampling and sample preparation, but also for further analysis.

Because municipal solid waste consists of so many different materials which vary in size, shape, density, hardness, degradability, etc., a problem exists in determining a representative sample. The composition of solid waste varies considerably throughout the day as well as the week and year. Each truckload of material arriving at the disposal site represents a different sample of waste. Indeed, the same holds true for different parts of the refuse in a collection truck, since the refuse may be collected from different types of waste producers. Therefore, it should be clear that a representative sample of refuse defines only the solid waste from which the sample was prepared; to construe otherwise could be foolish. Only when several representative samples are collected and analyzed can any kind of average characteristics be attributed to solid waste from a given location.

One must be careful during the sampling and sample preparation techniques not to alter the characteristics which will be measured later. For example, many recognized references on analyzing solid waste recommended the solid waste samples be finely ground, mixed and successively quartered, in order to obtain representative samples and to increase the accuracy and reproducibility [4-8]. Needless to say, these methods were not developed for most physical analyses, and cannot be used in this research.

Methods of Previous Investigators

Sampling

Sampling techniques vary because of variations in the characteristics of materials sampled, the forms in which it is available and the specific methods of analyzing the material. For example, the material may have particles which are fine, medium or coarse, and it may be in a pile, truck, or flowing on a conveyor belt. The American Society for Testing Materials (ASTM) standards [3] describe various sampling techniques, discussed in the following paragraphs.

One of the most accurate places to sample is where the material drops from a chute or conveyor belt. If the waste stream is small enough, a pail or other suitable container can be swung completely across the flow in a brief interval of time with a uniform movement to collect the sample. Under no circumstances should the sampling container be allowed to overflow, because this tends to reject a higher proportion of the larger particles.

It is extremely difficult to secure truly representative samples from a pile. This is especially true when the material contains large particles, since the particles tend to segregate during the placement of materials in the pile. It is unlikely this exists for raw solid waste after it is unloaded from a collection truck, because the method of unloading the trucks does not produce this type of segregation. The ASTM procedures recommended small random samples be taken from as many parts of the pile as accessible, and collected so the composite has the same grading as the larger amount.

The ASTM or similar sampling procedures are generally used and recommended by the various investigators or institutions working with solid waste. For example, in sampling compost, the Swiss Federal Institute for Water Supply, Sewage Purification and Water Pollution (EAWAG) recommended the samples be taken from as many parts of the windrow pile as possible and then mixed together [6]; the methods proposed by EAWAG are routinely used in Western Europe. De Groote [9] recommended equal amounts of compost (about 5 lbs.) be collected from different locations in a compost pile at a depth of about 20 to 30 in. Graduate students at the University of Florida obtained representative samples from a large pile at the Gainesville, Florida, composting plant by random sampling at four points of the pile with the bucket of a front-end loader [10]. The four samples, each about one cubic yard in volume, were then mixed together by turning the mixture with the bucket, being careful not to damage the particles. Approximately one-quarter of this mixed sample (328 lbs.) was removed with the bucket and set aside for composition analysis. Multi-samples were also collected by the project personnel at the Gainesville composting plant for chemical and composition analyses [11]. The samples were randomly collected from the conveyor belt. Winkler and Wilson [12] used various sampling techniques at Middleburg, Vermont, and Cambridge, Massachusetts. They found the most satisfactory method of obtaining a representative sample of manageable size was to take the material from a pile just dumped by a packer truck. They recommended that it be taken from the lengthwise side of the pile rather than from one end.

Instead of randomly choosing samples from a large refuse pile, a few investigators have used a quartering technique to obtain their initial samples from the complete pile. For example, Bell used this method on refuse piles of 1,600 lbs. or greater to obtain manageable samples for composition studies [13]. A few investigators have used complicated and time-consuming grid and quartering techniques to obtain samples from a truck load of refuse [14,15].

Representative samples also have been collected directly from the refuse source, e.g., homes and businesses [8,12, 16-18]. Bell [8] developed a method of sampling refuse in several cities (2,400 samples were collected during his study). Sample areas were selected by a stratified random sampling procedure after the city was classified into high, medium, and low socio-economic areas, on the basis of housing and/or property market value. Weekly samples of refuse were then obtained from the sample areas.

Sample Reduction

Since only small samples are required for laboratory testing, the usual procedure is to collect relatively large initial samples (gross samples) and reduce them to a suitable size for analysis (test sample), without impairing them in any way. The most common method described in the ASTM procedures [3] and by Allen [2] is to use the "coning and quartering" procedure in which the gross sample is placed in a cone by depositing each shovel-full of material at the apex of the cone, allowing it to run down the sides equally in all directions. This procedure allows the material to mix. The cone is then spread into a circle of uniform thickness and quartered. Two opposite quarters are rejected and the remainder is again mixed into a conical pile taking alternate shovels-full from the two quarters. This procedure is repeated until the sample is reduced to the required size.

Gross samples, if not too large, may also be reduced by one or more passes through a sample splitter or riffler which divides the sample in half (via a metal compartment containing many chutes) while maintaining the characteristics of the original sample [2,3]. By repeated passes, the sample can be split into quarters, eighths, etc., until the desired sample size is obtained. Unfortunately, the sample splitter is not reasonably adapted to material with large particles, because the passages in the splitter (chutes) should be at least three times as wide as the largest particle in the sample for it to work properly.

The ASTM sample reduction procedures appeared to be the standard way to reduce solid waste sample sizes. Many investigators have used the quartering technique [5,7,16,19]; one investigator used the sample splitter on finely ground refuse [11]. The American Public Works Association (APWA) recommended a modified quartering technique in which all of the initial quarters are rejected except for a shovel-full from each [4]. The four shovels-full are then combined, mixed, and quartered again. A 0.11 to 0.22-lb. sample is then collected from each quarter for repetitive analysis.

Size of Gross Samples

The size of the gross sample depends not only on the characteristics of the material, the form in which it is available and the requirements of the analysis which will be run, but also on whether the sample reduction methods will be used later. Thus the size of the gross sample can vary widely.

Needless to say, the size should be sufficient to allow one to run all of his analyses, including repetitions. Also, in order to obtain the needed accuracy and reproducibility, it is necessary to analyze larger test samples for materials with large particles than for finely ground materials. Thus larger gross samples were required for coarse materials, such as raw solid waste. Many investigators have drastically reduced the size requirements of their samples by fine grinding and thoroughly mixing the material. This can be done for chemical analysis, usually reducing the test sample requirements to less than a few grams, but it is not suitable for physical analysis.

The literature review indicated various investigators have used widely varying sample sizes for gross samples of solid waste. APWA [4] recommended relatively large initial samples (gross samples) be collected for most mixed refuse; a size of not less than 500 lbs. is suggested. The sample was then reduced by shredding and quartering until four samples were obtained, each about 0.11 to 0.22 lbs. in weight. Bell [8] used a gross sample size from 2.2 to 6.6 lbs. for chemical analysis. Higginson [7] recommended that samples submitted for chemical analysis (gross sample) be between 0.022 to 0.044 lbs. in size. A sample size (gross sample) of approximately 0.5 cu. yd. (100 lbs.) was collected for chemical and biological analysis at the Gainesville, Florida, composting plant, while sample sizes of 37 to 328 lbs. were collected for composition analysis [11,20]. EAWAG [6] recommended a gross sample size of 2.2 to 4.4 lbs. Gawalpanchi *et al*. [21] collected 7-lb. gross samples of shredded waste for particle size analysis; the size of the test samples was only 0.13 to 0.22 lbs. Klee and Carruth [22] found there was no significant difference (at the 5 percent risk level) between the precision obtained from a 200- to 300-lb. sample and the precision obtained from much larger samples in estimating refuse composition. The sizes of their samples for estimating composition varied from 200 to 1,700 lbs. Winkler and Wilson [12] used 175- and 600-lb. samples in their studies of refuse size characteristics.

Sample Drying and Storage

Samples should be immediately dried, not only to standardize the results, but also to prevent partial particle degradation due to biological action (if the samples are to be stored for any length of time). The method of choice is the oven-drying technique, preferably in a large convection oven. The ASTM standards [3] recommend all samples be dried to constant weight, usually at a temperature of 100° ± 5°C, except in those cases where such a temperature might have an adverse effect on the material.

Soils are usually dried overnight in 105 or 110°C ovens. Lambe [23] felt this difference of 5°C is of little practical importance in drying. He also presented curves to show the effect of temperature in drying five extremely different soils to indicate that soil is far from dry even at 110°C.

Pertinent data from his curves are provided in Table 1 to show the relative effect of temperature in drying compared to the 110°C drying oven. The effect of drying temperature was found to be less than 3 percent (1 percent of moisture-wet weight) over the 40°C range. As expected, colloidal soils showed the most variation in drying temperature, while sand showed almost no variation. Lambe also cautioned that elevated drying temperatures (105°C) may be high enough to decompose some types of organic matter in soils.

Table 1

Relative Effect of Temperature on Drying Soil [23]

	Relative Moisture Content (Dry Weight Basis)[a]						Range of Moisture Contents (Wet Weight Basis)[b]
	Drying Temperature (°C)						
Soil Type	70	80	90	100	105	110	
Ottawa sand	1.000	1.000	1.000	1.000	1.000	1.000	19.29
Boston Blue clay	0.994	0.997	0.997	1.000	1.000	1.000	24.70-24.81
Leda clay	0.971	0.980	0.987	0.993	0.996	1.000	30.41-31.03
Mexico City clay	0.976	0.980	0.985	0.994	0.997	1.000	77.06-77.48
Diatomaceous earth	0.972	0.981	0.980	0.992	0.995	1.000	85.92-86.25

[a] The "dry weight" moisture content is defined as the weight of the moisture removed by drying divided by the weight of the solids retained after drying.

[b] The "wet weight" moisture content is defined as the weight of the moisture removed by drying divided by the net weight of the material (solids plus moisture).

Lambe pointed out that drying time should depend on the type and amount of sample and the shape of the soil specimen. For example, he stated that a few grams of sand can be dried in an hour or less, whereas the same weight of fine-grained clay may require many hours. He also urged that the samples be cooled before weighing because hot containers encourage spillage and hot material can disturb the accuracy of a beam balance. A non-plastic soil may be cooled normally at room humidity, Lambe said, and a plastic soil can be treated in the same way if weighed within an hour or two after removal from the oven. He recommended that samples be kept in a desiccator for a longer period of time.

The methods outlined in APWA [4] also state that high temperatures (105°C) have an adverse effect on municipal refuse because they permit volatile fractions (other than water) to evaporate. Therefore, it recommended the refuse be dried to constant weight at 75°C in a forced-air circulation drying oven. It is also recommended that the material not be packed in containers during drying and the lids be cocked or removed. For samples with less than 60 percent moisture, it stated that drying for 24 hours in the forced-air oven was usually sufficient, but 48 hours was preferred. It was recommended that the material be cooled either in desiccator jars or cabinets with desiccator containers, prior to weighings.

Personnel at the National Environmental Research Center of EPA [5] apparently concur with this temperature because they recommended samples be dried in an oven 70 to 75°C overnight (or for 24 hours) or until the weight loss for an additional hour of drying is less than one percent of the total previous weight loss. They concluded that if the sample is small (3 to 5 lbs. for moist compost, or less for a bulkier material), the drying can be carried out conveniently in a large laboratory oven, but for large samples an industrial-size oven should be used. They recommended the material be cooled in a desiccator or covered with an aluminum foil prior to weighings.

Several other researchers also dried their refuse samples within this temperature range. Bell [8] found his drying time varied from 12 to 48 hours (depending upon the type of material) when drying refuse to constant weight at 70°C; the time was further reduced when the material was periodically stirred. Researchers at the Gainesville, Florida, composting plant, the University of Florida, and the University of Louisville dried their refuse samples for 48, 72 and 24-48 hours at 75, 70 and 70°C, respectively [10,11,16].

Many investigators, especially those in Europe, recommended a higher temperature for drying. Higginson [7] felt the samples submitted for chemical analysis should be dried to equilibrium at 80°C. The procedures of EAWAG [6] recommend that samples be spread thinly and dried at 105°C in a drying oven (preferably ventilated) until their weight becomes constant (no drying time was recommended). The samples are then allowed to cool in a turned-off drying oven and weighed immediately afterwards. Hafeli [17] recommended samples be dried in an oven at 103 to 105° for 24 to 26 hours. Gawalpanchi _et al_. [21] dried their refuse samples to constant weight for 18 to 24 hours at 104°C; only 0.44-lb. samples were dried by spreading them on glass pans and covering them with perforated aluminum foil.

It is often necessary to store samples for later analysis. When storing, it is important that the samples be protected from contamination so they do not absorb moisture; it is also important that parts of the samples are not lost. Various types of containers have been recommended. The procedures outlined in APWA [4] recommend dried solid waste be stored in wide-mouth screw top jars until needed. Bell [8] stored his material in air-tight cans. Air-tight plastic bags were proposed by other researchers as storage containers [6,11,21].

It is desirable to redry the samples when ready to use to eliminate any possible moisture the samples may have picked up. The APWA procedures [4] recommend the samples be redried at 75°C for at least two hours before using them.

Experimental Methods and Equipment

Sampling

In order to accomplish the objectives of this investigation, it was necessary to collect solid waste samples from four different sources, three from Gainesville, Florida, and one from Johnson City, Tennessee. The specific sources of waste sampled and their designation are the Gainesville, Florida, raw waste (R), discharges from the primary shredder (P) and secondary shredder (S) at the Gainesville compost plant, and the discharge from the rasp shredder at the Johnson City, Tennessee, compost plant (J).

Shredded refuse from the Gainesville compost plant was chosen basically because of the close proximity of the facility to the University of Florida (about a mile). In reality there were very few alternatives, because at the time of the research there were only a few operating shredders in the United States. Because of the earlier extensive research done at the Gainesville compost plant [11,20], it also was expected that each investigation would complement the other. Raw refuse was chosen from the City of Gainesville mainly because of convenience; it also was felt that the Gainesville waste represented typical municipal refuse. Shredded refuse from the Johnson City compost plant was chosen because it was from a completely different type of shredder, and was one of the very few shredder plants in operation in this country during the time of the research.

The ASTM sampling procedures [3] appeared to be the best or most suitable method and were followed in the collection of all waste samples at Gainesville; single randomly chosen samples were collected from the plant discharge pile at Johnson City for each sample from this source. The raw refuse samples at Gainesville were randomly chosen from a pile and the shredded wastes were collected from conveyor belts.

Ten samples of raw refuse were collected at the Gainesville land disposal site from September 2, 1971, to October 25, 1971. No two samples were collected on the same day. A description of the samples is found in Appendix A. The samples were obtained immediately after the refuse was emptied from the city's packer trucks and just prior to compaction by the landfill dozer. An attempt was made to obtain representative samples by randomly choosing three to five subsamples from the pile. Each was about three to five gallons in size and large and bulky items were avoided. The subsamples were combined to form the gross samples. Each was about two cubic feet in size. The samples were then transported to the laboratory in a 10-gallon plastic garbage container. They were immediately dried for several days in the oven. These raw refuse samples will be designated as R-1 through R-10.

The packer trucks apparently provided a very minimal compaction of the raw refuse, as most bottles were unbroken, cans and heavy plastic containers appeared to be only slightly deformed.

Initially, it was planned to collect the primary and secondary samples at the Gainesville compost plant on a random schedule. There was no intention of collecting two or more samples on the same day. Unfortunately, due to a hurried, unscheduled closing of the plant, it became necessary to collect nine primary and eight secondary samples all on the same day (August 10, 1971). This was just a few hours before the plant closed. These samples were collected only a few minutes apart. A short description of the Gainesville compost plant is found in Appendix B.

Fourteen samples were collected after primary shredding from April 29, 1971, to August 10, 1971. A description of these samples is found in Appendix A. These samples were collected from the conveyor belt just ahead of the first magnet. In order not to stop the plant operation, it was necessary to collect almost all of these samples by scraping the refuse directly from the moving conveyor belt. Three of the samples were collected when the conveyor was stopped by taking a swath across the full depth of the belt. Negligible quantities of paper were being removed at the picking belt during sampling, so these samples had essentially the same composition as the raw refuse. Each sample was approximately one to two cubic feet in volume and was transported to the laboratory in 20-gallon sealed plastic bags. The samples were immediately dried and stored in sealed plastic bags until used. These primary shredded samples will be designated as P-1 through P-14.

Fifteen samples were collected after secondary shredding from April 29, 1971, to August 10, 1971. A description of these samples is found in Appendix A. The samples were collected from the discharge of the tripper just prior to placing the shredded refuse in digesters. A cardboard box was placed for several seconds under the free fall of the waste to sample from the complete flow of the falling material. Both magnets and the sludge pump were turned off and paper was not salvaged during most of the sampling period, so the samples essentially had the same composition as the raw refuse. Each sample was approximately one to two cubic feet in volume. The samples were transported to the laboratory in sealed 20-gallon plastic bags where they were removed, dried and stored in sealed plastic bags until used. These secondary samples will be designated as S-1 through S-15.

During mid-June, 1971, Carlton Wiles, Project Engineer of the Johnson City compost plant, collected four samples of shredded refuse from his plant. The samples, all collected on the same day, were obtained immediately following the rasp. Sludge had not been added but metals and bulky materials had been removed. The 1-1/2 cu. ft. samples were each air-dried prior to sealing in dual plastic bags and shipped to Gainesville by air express. Upon arrival, each sample was immediately dried in the oven for several days, and placed in sealed plastic bags until they were analyzed. A short description of the Johnson City compost plant is found in Appendix C. These rasp shredded samples will be designated as J-1 through J-4. A summary of the samples utilized in this research is found in Table 2.

Sample Preparation

Nearly all of the previously cited investigators used two ranges of temperatures for drying refuse, 70 to 75°C and 100 to 110°C. Since several of them cautioned against utilizing the higher temperatures (because it might volatilize or

Table 2

Summary of Samples

Source of Samples	Location	Identification
Raw refuse	Gainesville Landfill	R-1 to R-10
Primary shredded refuse	Gainesville Compost Plant	P-1 to P-14
Secondary shredded refuse	Gainesville Compost Plant	S-1 to S-15
Rasp shredded refuse	Johnson City Compost Plant	J-1 to J-4

decompose some of the organic matter), the lower temperature range was considered appropriate and was generally followed. Two gravity convection drying ovens were utilized for drying the samples. The primary oven, a large Napco Model 1430, was purchased in order to readily dry the large, moist gross samples. A smaller Thelco oven was used for redrying and for standby service. A description of this equipment is found in Appendix D.

The drying procedures, as outlined in APWA [4], were considered appropriate for the samples and were generally followed. The only exception was that the samples were cooled on the laboratory table and not in a desiccator cabinet as recommended. This was done because no such cabinet was readily available (due to the large sizes of the samples). It also seemed unnecessary since the laboratory was dehumidified and the samples were analyzed immediately after cooling.

The gross samples were dried immediately after they were received at the laboratory. Since most of the samples were not completely analyzed until quite a while later, it was important to remove the moisture so the refuse would not degrade during storage. All of the samples were heated at least two days, and usually longer, until they were dry. Most of them were first dried in the Napco oven which was vented to an exhaust hood. The temperature was maintained at 70 to 75°C in the oven throughout the drying period. The refuse was heaped (up to 4 in. high at the center) on 18 in. x 26 in. x 1 in. deep metal trays. The drying was enhanced by gently mixing the material periodically during the drying period.

Emergency drying procedures were adopted after August 10, 1971, when 17 primary and secondary shredder samples were collected on the same day. Normally, the two ovens were adequate for drying one to three gross samples at the same time. In order to prevent any degradation to the particles, it was decided to pre-dry the samples before placing them in the ovens. This was done on the roof of the laboratory during a very hot period. The samples were dried for about four hours and were periodically mixed gently to improve the efficiency of drying.

The samples were removed from the roof and sealed in plastic bags until the ovens became available again (up to one week later). At that time they were dried in the ovens for about one-half day, replaced in plastic bags and sealed until all of the samples received the initial oven drying. They were then redried in the oven for about one day, placed back in the bag and sealed until it was time for the analysis.

All raw samples were immediately analyzed after the initial drying period which varied from two to four days. The shredded samples were placed in large tagged plastic bags and sealed until a later date when they they were analyzed further. All of the shredded samples were further dried at 70 to 75°C for another day just prior to their analysis. Thus, almost all of the samples received two to four days of drying time.

The material from the oven was emptied in a pile on a clean floor just prior to analysis. Usually, the pile was quartered, being careful that all of the fines were swept to the proper quarter. Randomly (by flipping a coin), a quarter of the sample was chosen for the particle size analysis. Two of the other quarters were randomly chosen for the compressibility tests. The last quarter was kept in reserve or for "make-up," in case one of the quarters did not have a sufficient sample size. Sometimes the original sample size was too small to permit this procedure. In those instances, the sample was divided into only two or three fractions, using the same general procedures, rather than being quartered.

The preparation of the raw samples did not completely follow the above procedure. Since the complete raw gross sample was analyzed for particle size and composition, it was necessary to wait until those analyses were completed before the compression tests could begin. It was necessary to reuse the sieve analysis sample for the compression test.

The quartering procedure of the raw refuse was somewhat different because of the overly large sized particles in these samples. First, since the particle size and composition analyses were completed, one quarter was not needed for this analysis. Secondly, because the particles above one inch in size were always small in number, but large in weight, it was felt the quartering procedure should be modified. It appeared a more representative sample could be obtained by using the quartering procedure only for those fractions less than one inch.

Those fractions of the sieve analysis less than one inch were emptied into a pile on a clean floor, gently mixed, and then quartered. Those fractions greater than one inch were divided by hand, by placing into each of the above quarters a similar number of particles of each component for each size range. For example, the tin cans in the 2 in. to 4 in. size fraction were manually divided so the same number of cans were placed in each quarter. In effect, an attempt was made to obtain the same percentage of weight for each component of each size range in each quarter to insure the same total weight of each component. Each quarter was then gently mixed prior to use in the compression test.

It was necessary to modify the raw samples (except for R-10) in order to use them in the density and the compression analysis. This was because the large particles (8 to 16 in.)

were either too large for the compression test cylinder or only one or two particles existed in this size range, thus producing test samples which were not representative of the gross sample. It was felt these large particles would disproportionately influence the compression tests. In order to overcome this problem, the large particles were physically removed from samples R-1 through R-7. In samples R-8 and R-9, the large particles in the 8-to 16-in. range consisted only of cardboard and paper. Thus these particles were cut to form 4-to 8-in. particles. The composition and screen analysis data were modified accordingly when used with the compression data. With respect to sample R-10, it was felt the particles in the 8-to 16-in. range were sufficient in number and small enough not to overly influence the compression test results. Thus, this sample was not modified. For clarity, the particle size and composition analysis data for the raw samples, which will be used with the compression data, were designated R-1M through R-10M.

CHAPTER III

PARTICLE SIZE ANALYSIS

Introduction

Prior to the beginning of this research (1971), there were very little published data on the particle size analysis of solid waste. Many articles mentioned the particle sizes of certain types of solid waste, but it was obvious most of the authors used subjective measurements, based either on the maximum grate size of the shredders or a "visual measurement" of the larger pieces of refuse. At any rate, this practice has changed considerably within recent years and several investigators have reported good quantitative research on the particle size analysis of municipal refuse. Unfortunately, the published data are not sufficient for information on analytical techniques, precision, and accuracy for a proposed standard method.

Before we can define particle size analysis techniques, the terms "particle" and "particle size" must be unambiguously defined. In a classical sense, an individual particle is defined as a minute unit of matter whose size and shape depend on the forces of cohesion. A group of two or more individual particles held together by strong chemical forces is defined as an "aggregate." Aggregates are commonly found in chemical precipitation processes; they are stable with normal handling, stirring and shaking, but are broken up more or less readily by shear stresses. An "agglomerate" represents larger groups of individual particles or aggregates. Agglomerates commonly occur in sieving or drying operations [24].

In the case of many materials, the term "individual particle" is rather arbitrary since the particle size depends on the degree of disaggregation imparted on it during testing. A more rational definition is desirable for solid waste. Winkler and Wilson [12] defined a particle (or object), in measuring the sizes of solid waste particles, as those items which would be expected to remain intact, even after a reasonable amount of mechanical handling. They tested "border-line" particles by lifting the questionable part, and if it broke apart it was considered separate particles. They also emptied bags and inverted containers for a second and the portion of contents which fell out also was considered separate particles. Newspapers consisting of several sections, folded one within another, were considered as single particles. In practice, they seldom found this definition as ambiguous.

Particle sizes are defined in terms of the method by which they are measured [25]. Ideally, the size of a particle is that representative dimension which best describes its state of subdivision. For a spherical, symmetric particle, the diameter is obviously that dimension and thus its size. Only in the case of a cube or a sphere can the size of a particle be completely described by one parameter.

Unfortunately, the particles the analyst must measure are rarely these shapes; in addition, the size range of the particles in any one system may be too wide to measure with any one measuring device [2,26].

In small particle analysis, all of the analytical techniques, except one (microscopy), measure only one dimension. However, the mean ratio of significant dimensions for a particulate system may be determined by using two methods of analyses and finding the ratio of the two mean sizes. This proliferation of measuring techniques is due to the wide range of sizes and size dependent properties which have to be measured [2].

Derived diameters are determined by measuring a size dependent property of the particle (such as volume or particle settling rate) and relating it to a linear dimension. Thus, a unit cube has the same volume as a sphere with diameter of 1.24 units, hence this is its derived volume diameter [2].

Derived diameters can also be provided for irregular particles, usually found in solid waste. The diameter of a particle deviating from spherical symmetry, may be defined as any one dimensional distance between two points on the external surface of the particle which intersects the center of gravity of the particle. A large number of non-equivalent diameters satisfying this definition are possible for an irregular particle. The distribution of these diameters is continuous between an upper and lower limit. Therefore, the size of any irregular particle is a statistical average of all those non-equivalent diameters. Consequently, when this method is used the size of a given particle depends on the averaging method [26].

The diameter of an irregular particle in some preferred direction is meaningless when applied to a single particle, although it is valuable when applied to a large number of particles in random orientation. Such diameters are known as statistical diameters. Mean diameters may be derived from graphical or statistical treatment of size distribution data or statistical treatment of secondary size characteristics such as surface area [2].

When the sieve analysis is used the size of the particle is defined as the minimum aperture through which the particle passes. In reality, because it is impossible to have an infinite number of screens, the particle size is specified as the smallest sieve aperture through which the particle passes and the size of the following aperture through which it fails to pass [27,28]. Fractionation by sieving is a function of two dimensions of the particle only, maximum breath and maximum thickness; for unless the particles are excessively elongated, the length does not hinder the passage of the particles through the sieve aperture.

Sieves classify particles according to geometric similarity, regardless of the density. Both the shape of the particle and the shape of the openings affect the size of the particles which can pass through a given opening. For example, a particle in the form of a thin square plate can, in principle, pass through a square hole of side "L" if the length of the edge of the plate is less than $L\sqrt{2}$. However, the probability of this plate passing through such a hole (when it is adjacent) is quite small because of the small probability that it will be properly oriented [25].

Methods of Previous Investigators

Introduction

The trend of particle size research in the past was directed toward micro-analytical techniques. There is a wealth of information on measuring the sizes of small particles and their subsequent interpretation [2,24,27,29-31]. Although the measuring techniques appear to have limited value for most forms of solid waste, the statistical and graphical methods of evaluating and presenting the data were found valuable. Methods commonly used in small particle analysis are microscopy, wet and dry sieving, sedimentation, elutriation, centrifugation, Coulter counter, light-scattering, permeametry and gas-absorption. Several of these methods indirectly measure the size of the particles by suspending them in a liquid medium; this is unacceptable for municipal refuse if we want to know the dry size of the particles (since the liquid medium would alter the particles). Many of the methods are also time-consuming since they directly measure each particle separately. The only method in small particle research which appears applicable to municipal refuse is sieving.

Sieving is probably the easiest and certainly the most popular method of size analysis in the industrial field. In fact, it is a standard procedure for soil analysis [23]. It is restricted to materials having the greatest proportion coarser than 60 to 75 microns and is used almost exclusively for materials above this size. Sieve analysis can be completed in a relatively short time, requires little operator skill, is a reasonably accurate technique, and involves relatively inexpensive equipment [2,3,25,29].

A sieve is an open container, usually cylindrical, having definitely spaced and uniform openings in the base. The openings are usually square and constructed from wire mesh. The sizes of the screen openings have been standardized, and two standard series are used in the United States, the Tyler Standard Scale and the United States Sieve Series. By stacking the sieves in order of ascending aperture size and placing the material on the top sieve and shaking or agitating for a predetermined time, the material is classified into fractions. The particles having a dimension smaller than the sieve openings are allowed to pass through while larger particles are retained on that respective screen. A pan is placed at the bottom of the stack to collect the fines and a lid is usually placed on top of the screens to prevent loss of material. The method of agitation may be either manual or mechanical but mechanical shakers generally give more dependable results because of their reproducible action. The portion of the sample retained on each sieve is weighed [2,3,23,25,26,29] and commonly expressed as the percent by weight of the sample retained on that screen or the percent by weight passing the sieve in question.

The apertures of a sieve may be regarded as a series of gauges which reject or pass particles as they are presented at the aperture. The probability that a particle will present itself at an aperture depends on the following factors [2,32]:

(1) particle size distribution of the material;
(2) number of particles on the sieve;
(3) physical properties of the particles;
(4) method of shaking the sieve;
(5) dimension and shape of the particles; and
(6) geometry of the sieving surface (e.g., open area/total area).

Whether or not the particle will pass the sieve when presented at the sieving surface depends on its dimension and the angle at which it is presented.

The distribution given by a sieving operation also depends on the following variables:

(1) duration of sieving;
(2) variation of sieve aperture;
(3) wear;
(4) errors of observation and experiment;
(5) errors of sampling; and
(6) effect of different equipment and operation.

Because of the many variables which can influence the particle size distribution, it is imperative the results be standardized; this is especially true for the finer sizes. Not only should equipment be standardized, but also the size of the test sample, method of shaking, time of sieving, etc. ASTM has adopted a number of standards using sieves for particle size analyses on specific materials, and some appear to be readily adaptable for solid waste [27,28,33,34].

ASTM also published a manual titled, Manual on Test Sieving Methods [3], which was intended as a supplement (not a substitute) for the many published ASTM standards relating to sieve analysis of materials. This manual brings together, from many sources, proven methods of sieve analysis. It states:

> . . . because of the widely different properties of the various materials to be sieved, such as size of particles, density, moisture, hygroscopic properties, particle shape, friability, abrasiveness, cohesiveness, etc., it is not possible to specify a single procedure to follow in making all sieve tests. Fortunately, standard sieve test procedures have been established for many important materials and groups of similar materials, and, whenever such standard procedures exist, it is important that they be followed to the letter by all laboratories or individuals making sieve tests of the materials the standards cover. . . . In spite of the considerable standardization work that has been done, there are hundreds of granular materials for which sieve analysis data are desired but for which standard test procedures have not been established or published (p. 1).

There are two ASTM standards which appeared to be reasonably adaptable for solid waste: ASTM Designation C 136, "Test for Sieve or Screen Analysis of Fine and Coarse Aggregates"

[33], and ASTM Designation E 389, "Test for Particle Size or Screen Analysis at No. 4 Sieve and Coarser for Metal Bearing Ores and Related Materials" [28]. Both have very similar methods but the latter accounts for large particles and highly friable materials. Since screens were not available for particles over 4 in., it was necessary to classify each large particle by direct measurement.

Refuse Particle Size Analysis

Prior to 1970, most of the work in defining the size distribution of municipal waste was done in Europe. Although many researchers have published their results, there is very little description of their analytical procedures. All appeared to use some form of screens.

One of the earliest analysis of refuse was done by Dezso and Jeno [35] at Budapest, Hungary. The results provided in Figure 1 were obtained on both winter and summer raw refuse. The results represented seasonal trends in refuse where combustibles were burned at homes in the winter and large quantities of ashes were found in the municipal waste. The analytical procedures were not described.

A quantitative and qualitative program for refuse was established in Great Britain in 1961 in an effort to define the yield and composition of raw refuse [7,18]. Large hand and vibrating screens were used to classify the refuse dust (e.g., the material which passed the 1/2-in. screen). The results are provided in Figure 1.

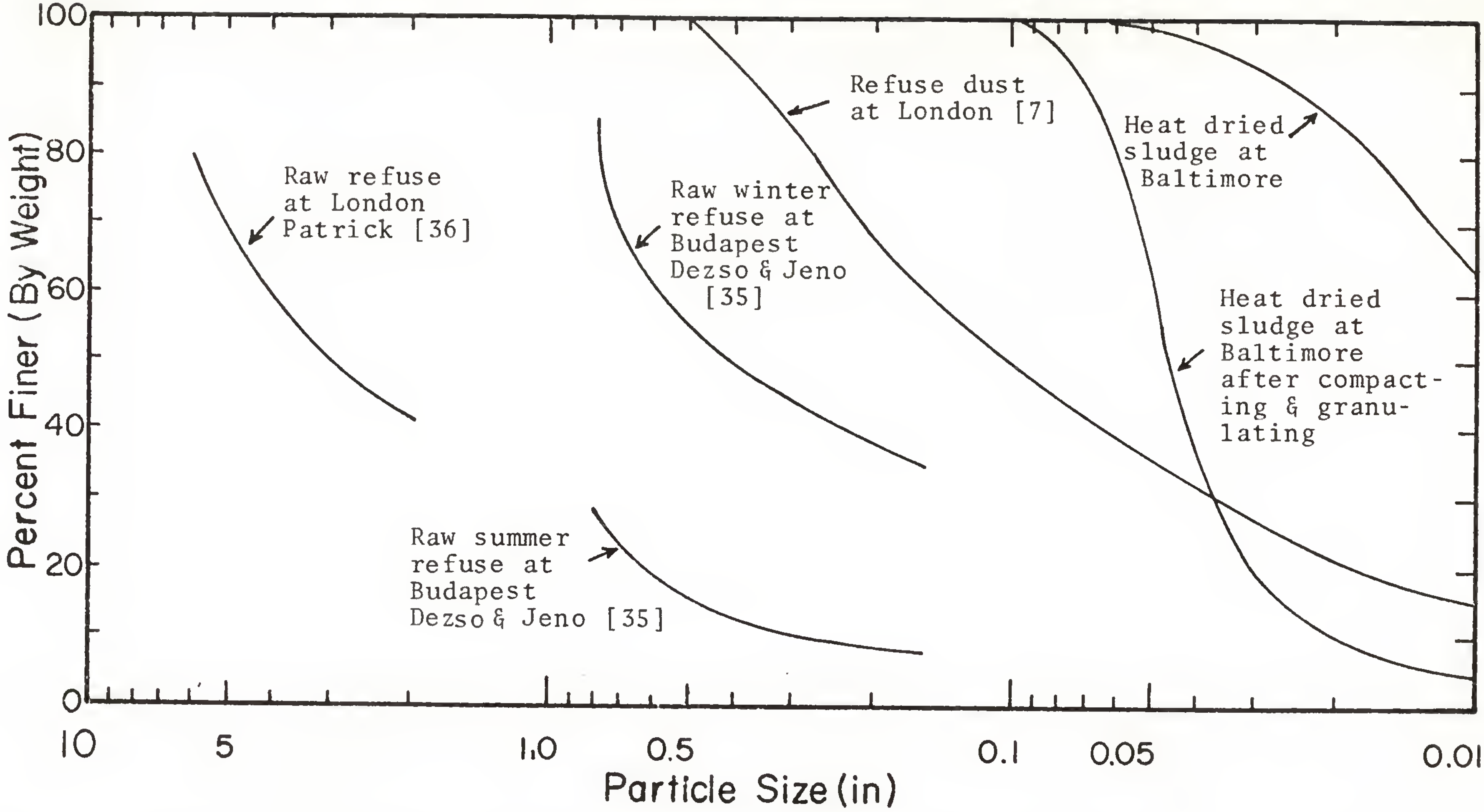

Figure 1. Particle size distributions of various types of waste.

Patrick [36] reported a large rotary screen (7 ft. 8 in. diameter) was tested in London to grade refuse for later shredding in hammermills, thereby eliminating the need for manual picking. The screen was formerly a part of a Volund drum-type shredder with the beater arms removed. Two sets of screen plates were installed in the drum; the upstream half was provided with 2-in. diameter holes, while the second section consisted of 144 holes, each 7-1/8 in. x 5-7/8 in. in size. The screening results on typical domestic refuse are presented in Figure 1.

The particle size distribution of shredded waste was determined by Rena [37] at Dundee, England. The refuse, shredded by a 200-horsepower Jeffrey-Diamond hammermill rated at 20 tons per hour, was fed to compactors. The results of the analysis are provided in Figure 2.

Several other Europeans have also provided size analysis of solid waste. Finnie and others [38,39] reported a 50-ton per hour hammermill shredder at the Newham barge transfer depot in London was capable of reducing raw refuse so that 90 percent passed a 2-in. screen and 25 percent was below 1/2 in. Finnie [38] also stated the product from a rotating cylinder type shredder produced a finer product than that of a hammermill. The 50-ton per hour hammermills at Cringle Dock in London were specified to insure at least 80 percent of the material passed a 1.75-in. screen and the remaining 20 percent measured no more than 6 in. [40].

Several European researchers have recommended screens be used in the laboratory for analyzing refuse. Hafeli [17] recommended refuse be screened through 0.197- and 0.984-in. screens and material greater than 0.984 in. be separated by hand into combustible and non-combustible fractions. Four subfractions were thus provided on which individual analysis can be run. Hafeli felt the division of waste into these four subdivisions produced more reproducible results. Novak et al. [41] screened refuse through a 0.787-in. rotary sieve and then through 0.197- and 0.079-in. screens. Various chemical and physical analyses were then determined on each fraction, except for the fraction greater than 0.787 in. Screens also have been proposed to determine the amount of foreign matter (glass, ceramics, metals, etc.) in compost [42]. A 6.6-lb. sample was screened through a standard sieve with 0.268-in. round holes. The residue was hand-sorted to determine the weight of each classification. A larger sample (22 pounds) was recommended for compost used in agriculture. Sifting was done through screens having 0.748- and 0.535-in. holes. The permissible amounts of foreign matter depended on the purpose for which the compost is used. Horstmann [43] proposed screens be used to determine the rapidity or degree of decomposition of compost. He reported the screenings through 0.236- and 0.984-in. mesh sieves showed definite differences in the quality of compost. One study showed green compost, having a particle size greater than 0.236 in., constituted about 75 percent of the total mass of processed waste.

Following decomposition, this amount was decreased to about 12 percent.

Very little research was done prior to 1970 in the United States in developing methods or defining the particle size distribution of solid waste. One of the earliest research studies published was on food waste ground in garbage grinders. Baumann *et al*. [44] proposed a procedure for determining the particle size of ground garbage, which involved the suspension of the material in a volume of water sufficient to facilitate the passage of particles through a set of sieves. Detergents were used to cut the grease in the garbage. More than 300 tests were conducted to determine the particle-size distribution of ground garbage. Cohn [45] also researched garbage grinders and recommended the home garbage grinders shred the food waste sufficiently so that 100 percent would pass a 1/2-in. screen, at least 90 percent pass a 1/4-in. screen, and not over 5 percent pass a No. 40 sieve.

A sieve analysis was run on various types of heat dried sewage sludge in Baltimore to determine the efficiency of processing equipment [46]. Due to the excessive amount of dust and finely divided particles in its dried sludge, the City found it difficult to sell its product or to encourage its employees to work around the material. The City was interested, therefore, in equipment which produced granules from the material (compactor, granulating mill, and vibrating screens). The screen analysis of the tests is found in Figure 1. Their analytical procedures are not known.

Oberaker [47,48] experimented with various types of screens to determine the size distribution of shredded waste. To help overcome the diversity in flexibility and rigidity and the agglomeration of various size particles, he attempted to keep the refuse mixed with jets of air. He proposed this would keep the material suspended in a gentle stream of air and also would allow for sufficient tumbling and mixing to break up the clumps. The gentle air flow, he theorized, would allow all of the lighter particles to float upwards while, at the same time, not force larger particles through smaller screens.

The initial design was a tall, thin box with six screens having openings ranging from 1/16 to 1-1/2 in. The larger screens were placed on the bottom, several inches above a small blower. The refuse was placed between the blower and the screen. The air flow blew the lighter fractions (paper, plastics, cardboard) upward through the screens. Ports were provided on the side of the box to insert an air-jet to keep the material mixed. After several test runs, however, the results were found to vary widely. Many of the lighter, more flexible particles were blown through screens smaller than their actual size. When the air-flow was reduced to prevent this, the air-stream was insufficient to suspend the heavier pieces, including cardboard and wood fragments. Glass, metal, and rocks were completely unaffected by the blower, regardless of the air-flow.

After modifying the original design to correct these deficiencies, the final design consisted of a wooden box 6-3/4 in. x 4-1/2 in. x 5 ft., with a series of six screens with openings from 1/16 to 1-1/2 in. The largest screen was placed at the top for this design and the smallest at the bottom. A blower was attached at the top of the box to provide a very gentle downward air-flow. The flow kept the small fibrous dust from clinging to the larger particles. Ports were again provided, but this time they were positioned below the screens and aimed upward so that the air-jet would strike the screen from the bottom and keep it from becoming clogged. The front side was hinged to allow access to the screens and had windows for observation.

Test runs were conducted with residential refuse which had been ground in a horizontal hammermill and dried. The dimensions of the box limited the sample size to approximately 14 gms. The samples were placed in the top of the box and the blower was adjusted to provide a very small flow. The samples were then hit with a jet of air and allowed to fall downward through the screens. Jets of air were used on each screen until it appeared that only particles larger than the screen openings on which they rested were present on each screen. The total time for one run was between five and eight minutes. The average results of seven tests runs are presented in Figure 2.

Oberaker suggested several modifications to improve the performance of the screens:

(1) Increase the unit screen area from approximately 28 sq. in. to 100 to 150 sq. in., in order to give increased reproducibility and accuracy.

(2) Provide additional screens to reduce the need of interpolating.

(3) Provide smoother walls to prevent the lighter particles from clinging.

(4) Reduce the air-jet pressure in order to prevent the breaking-up of the particles.

Oberaker [48] also experimented with a rotary drum screen to determine the particle sizes of shredded refuse and certain components of the refuse. A 55-gallon drum with both ends removed was used. Screens were clamped to one end in successive order. The drum was constructed so that its axis could be adjusted from 10 to 45° from the horizontal. During operation, it was rotated slowly about the chosen axis angle. An angle of 25 to 30° was found to be optimum. A good screening action was provided at this angle and the best self-cleaning of the screens was obtained. Coarse screens were used first and the material which passed through was then re-screened with a smaller screen. This was done consecutively until the smallest screen was used. Five different screens were used (1/8 to 2 in.) and the samples were placed through the open-end of the drum directly on each screen. The particle size distribution results were not provided.

Fess [49] attempted to use visual and photographic methods to determine the particle size of processed refuse from the Gainesville compost plant. During the visual trials, shredded refuse was spread on a sheet of paper alongside a rule, and an estimate was made of the sizes of the pieces. The middle dimension of each particle was considered to be the size of the particle, e.g., the width. Fess then attempted to count the particles in the various interval widths, e.g., 1 to 2 in., 1/2 to 1 in., etc. This method presented certain problems because: (1) particles below the top layer of material could not be measured; (2) there were too many paper particles which were on their sides, thus their widths could not be measured; and (3) the smaller particles were too small and numerous to be counted. This method was soon abandoned.

During the photographic trials, Fess spread the refuse in thin layers so that many of the particles could be observed. As before, the larger particles hid the smaller ones and those below 1/2 in. were too small and numerous to count. Also, the small size of the sample introduced accuracy and reproducibility errors. Even though hand sorting of the larger particles allowed the smaller particles to become visible, they still were too small and numerous to count. Fess did not obtain a usable particle size distribution of any sample using this method and it was soon abandoned.

The author collaborated with Fess in a preliminary investigation using screens to classify processed refuse [49]. All screenings were made on the Gilson Mechanical Screen, Model CL 325, which was designed primarily for coarse aggregate from No. 4 to 4 in. in size. It had a capacity of 1 cu.

ft. of material, and was capable of classifying seven fractions at one time (see Appendix D for a description of similar equipment). Each screen had interior dimensions of 23 in. x 15 in. x 3 in. and the equipment provided vibrations primarily in the vertical direction with an amplitude of about 1/2 in.

Fess used 8 Gilson sieves in his research, ranging from No. 16 to 1-1/2 in. Processed samples from the Gainesville compost plant were collected after the primary and secondary shredders, immediately after the digesters, and from a mature compost pile. The latter two samples represented the effect of biological action on degradation of waste, as the digested waste was allowed to decompose about six days and the mature compost had been allowed to decompose two years. The mature compost also received a final shredding. The five different types of waste were air dried and screened, basically using ASTM Method C-136 [33]. The volume of each sample was approximately 0.6 cu. ft., and the samples were placed incrementally on the top screen during the screening process. Each sample was screened for five minutes. It was found that most of the screening was done after one to two minutes. Considerable fluffy material on the No. 4 screen resisted breakup and undoubtedly more material was left there than should have been. On several occasions certain smaller screens became too full and it was necessary to divide that fraction and run each half separately. The particle size distribution of the samples is provided in Figure 3. In summary, Fess concluded the screen was the best method for determining the particle size distribution of shredded waste. Although the Gilson was designed for 1-cu. ft. samples, he felt this was too large, and recommended samples no greater than one-half this size be used.

Fess [50] also worked with the author in analyzing and evaluating early samples collected for this research. The samples which he evaluated (P-1 to P-4 and S-1 to S-6) averaged 3.448 and 4.224 lbs., respectively. Since the samples, sample processing, analytical techniques, and results of the individual samples will be reported later, only his statistical evaluation will be presented here. Fess calculated the median particle size for each sample and the population medians. The results were:

Type of Sample	Number of Samples	Median (in.)	Standard Deviation (in.)
Primary	4	0.804	0.273
Secondary	7	0.422	0.162

He concluded (using the statistical t-test) the two medians were different at the 95 percent confidence level; thus the data showed the secondary shredder further reduced the particle size.

Jones [51] determined the particle size distribution of waste shredded by a Roto-Shredder Model 12. This mobile self-propelled machine straddled and traveled the length of the windrows of unsorted refuse. A revolving drum (with cleats on its periphery) ripped and shredded the material. This machine was very similar to the Cobey windrow turner used at the Johnson City compost plant (see Appendix C). Four metal frame sieves (each 18 in. x 24 in. and with effective openings from 3/4 to 7 in.) were used to screen the waste. Representative samples of 8 to 10 lbs. were analyzed. It was not stated whether the samples were dried. Fourteen samples were analyzed at two different drum speeds and two different number of passes over the windrows. The results are provided in Figure 2.

Trezek [52] discussed the size distribution of various types of shredded waste, including the data collected at Madison, Wisconsin [19]. He presented the size distributions of waste produced by two additional shredders (hammermill and a vertical shaft shredder), as well as the size distribution of waste shredded with different moisture contents (Figures 2 and 4). Both of the shredders were small in size as the hammermill was rated at 0.5 tons per hour and the Eidal vertical shredder was 2.5 tons per hour. The analytical techniques were not described.

Researchers at Sulfur Springs, Texas [53], screened shredded residential waste using both single milled and double milled refuse samples. The single milled samples represented refuse which was passed once through a flail mill while the double milled samples were passed through twice. Flail mills are a type of shredder in which chains (or flails) are attached to the rotor. The swinging chains are responsible

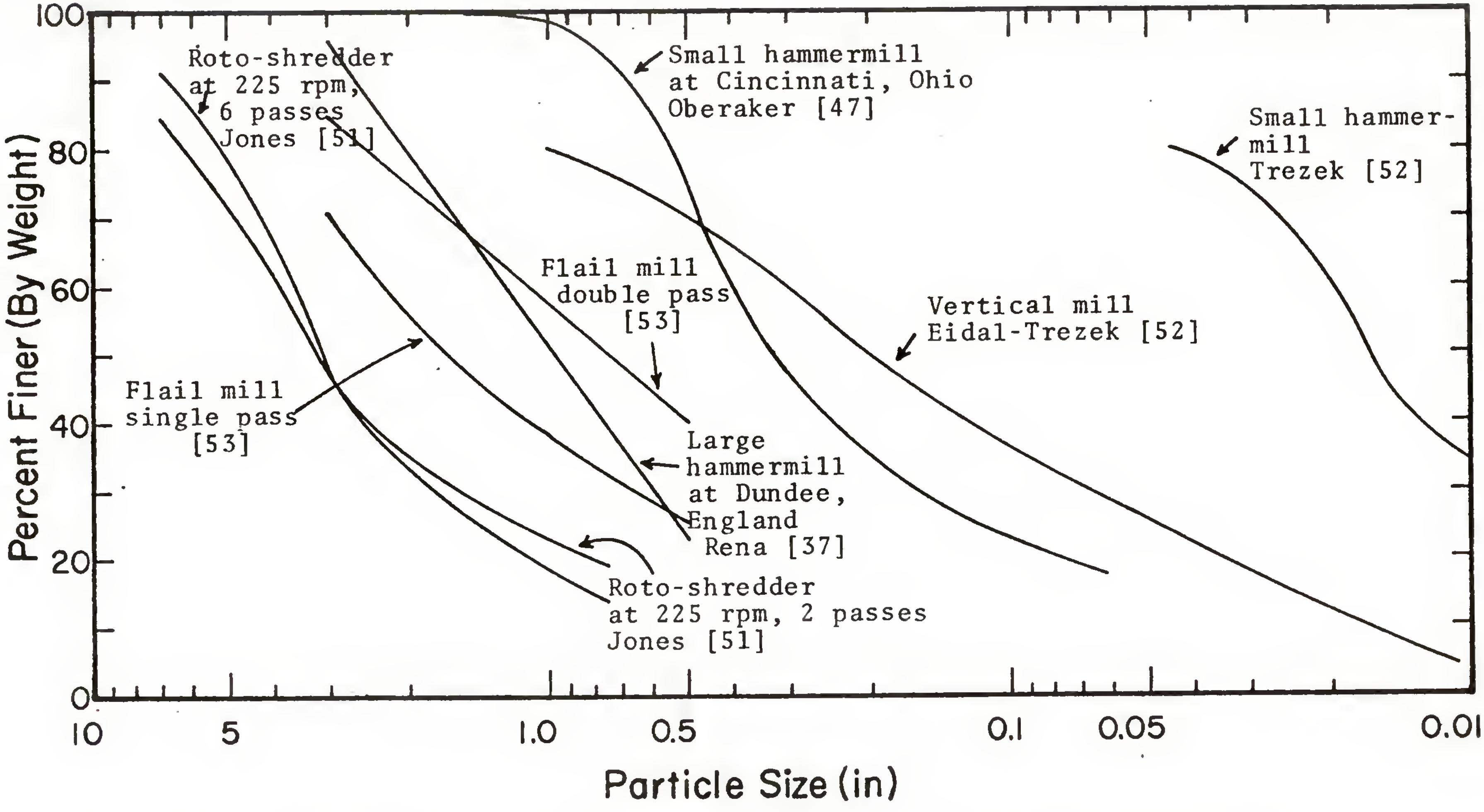

Figure 2. Particle size distributions of various types of shredded waste.

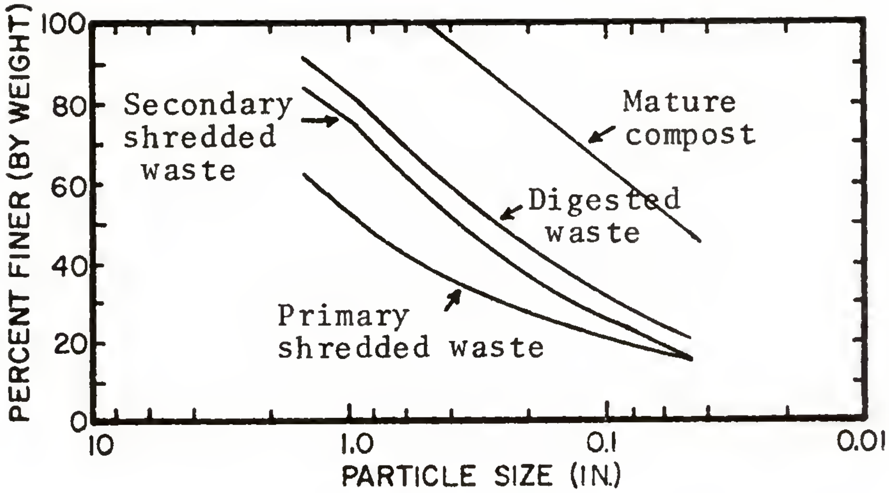

Figure 3. Particle size distributions of compost and shredded waste at Gainesville, Florida [49].

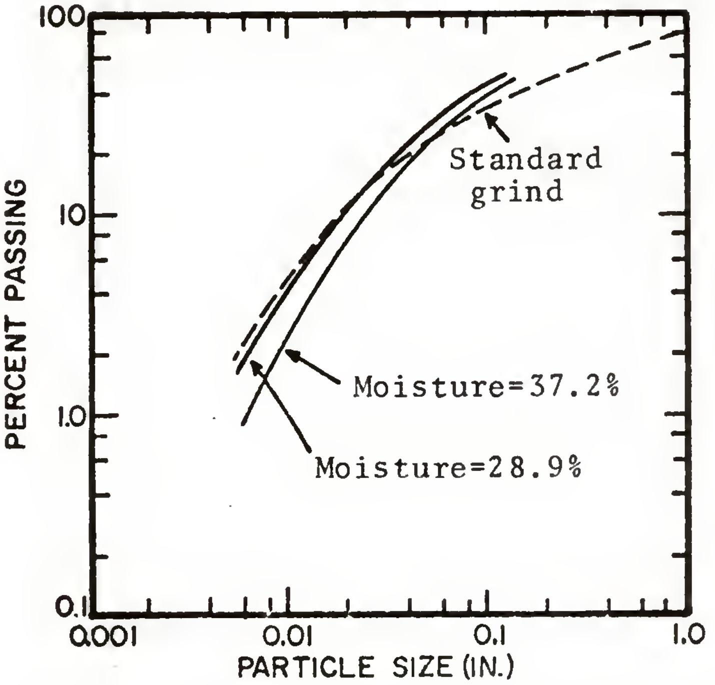

Figure 4. Comparison of moisture content on mini-shred setting on an Eidal Shredder [52].

for reducing the refuse. The shredder used in this research had two rotors, each powered by a 40-horsepower motor. Four sets of articulated flails were provided for each rotor at 90° spacing. There was only a 1 in. clearance between the swinging flails at the closest point of travel. The shredder also was provided with breaker bars and the samples were milled at about 24 tons per hour.

Three screens (3 in., 1 in., and 1/2 in. openings) were used to determine the particle size of the two samples (126 lbs. for single milled and 162 lbs. for the double milled). The screens were each 3 ft. x 3 ft. and were used in decreasing order. A drop cloth was used as the pan. Further details of the screening procedures were not provided. The results are shown in Figure 2.

Winkler and Wilson [12,54] determined the size of individual particles of raw solid waste by actually measuring them by hand with a ruler. All three dimensions were recorded, as well as the material's composition and weight. Since a great many objects were not rigid, they noted the dimensions were somewhat elusive to define. Flexible or collapsible objects were simply dropped on the measuring table as found and measured. They felt this was appropriate since it probably approximated a general mechanical handling system better than any other measuring scheme. The samples which they examined were collected from Cambridge, Massachusetts, and Middlebury, Vermont. Most of the samples were collected during the winter and were not dried. The composition of the wastes was expected to be somewhat different than others since both communities had very active newspaper recycling programs and Cambridge used a separate collection for food waste. In the course of the study, approximately one ton of refuse was examined by hand on an item-by-item basis. Only objects with at least one dimension greater than 1 in. were examined; the rest were not categorized and were termed "Miscellaneous and Uncategorized." This category was found to be 15 to 20 percent of the total weight.

The data were classified into nine major categories and fifty minor categories; the size data were classified in 1-in. increments from 2 to over 20 in. Cumulative number and weight distributions of the particle lengths were developed (Figures 5 and 6). Figures 7 and 8 are similar to the preceding pair of figures, but here the number and weight of objects, which will pass through a wire screen of various sizes, are shown. These figures are based on the criterion that in order to pass through a given mesh, an object must have at least two dimensions smaller than the mesh size. This amounts to 100 percent screening efficiency without any particle deformation. Actually, vibrating screens might pass somewhat fewer objects, except for flexible items such as paper and textiles, which might pass through a smaller mesh.

Sieve analyses were made on shredded refuse at Madison, Wisconsin, using the techniques and sieves utilized for aggregate analysis [19]. The refuse was shredded through an 8 ton per hour Gondard horizontal hammermill using a grate spacing

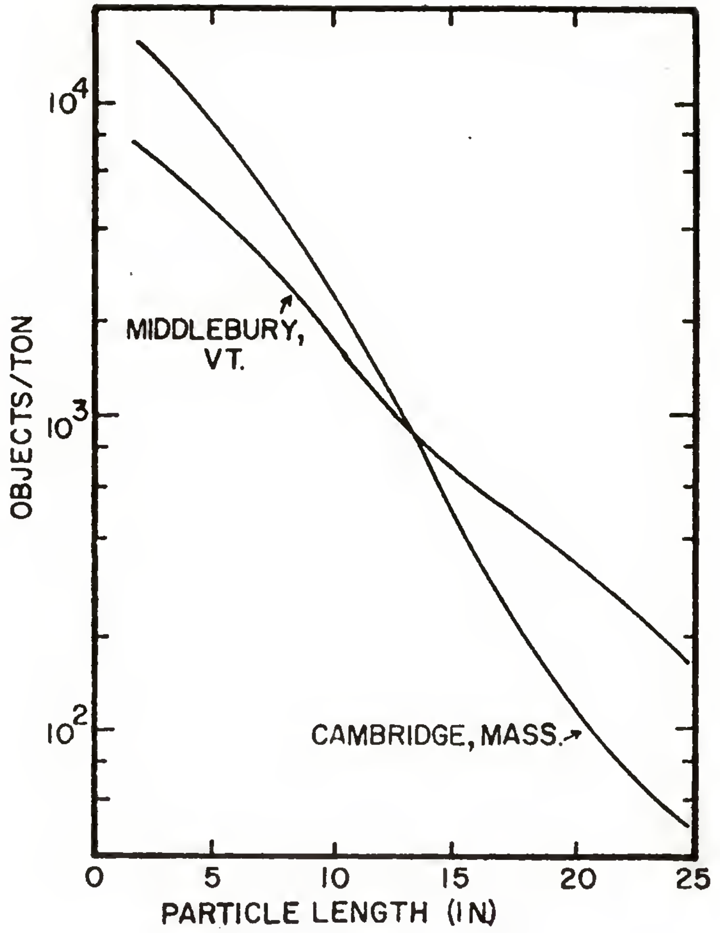

Figure 5. Cumulative number of objects per ton of raw refuse with longest dimension greater than given lengths [12,54].

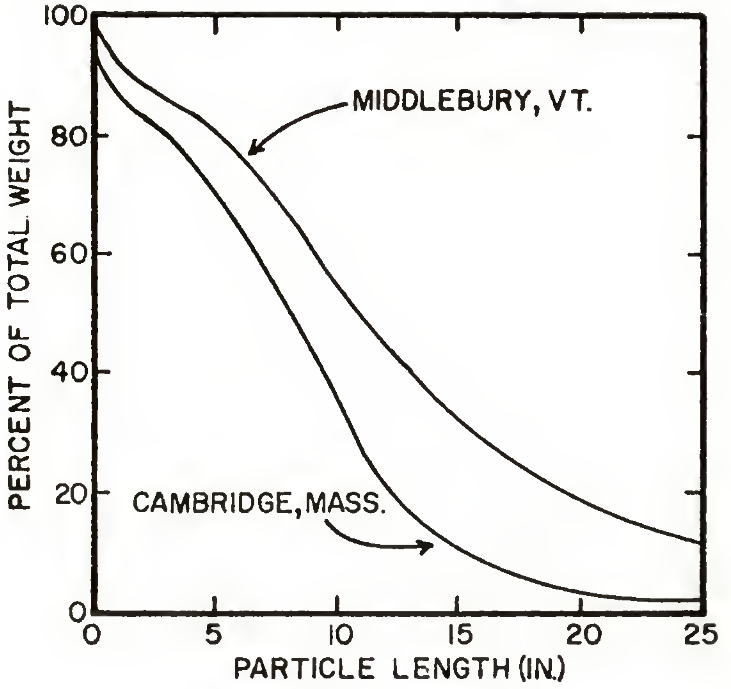

Figure 6. Cumulative weight (percent raw refuse total) of objects with longest dimension greater than given lengths [12,54].

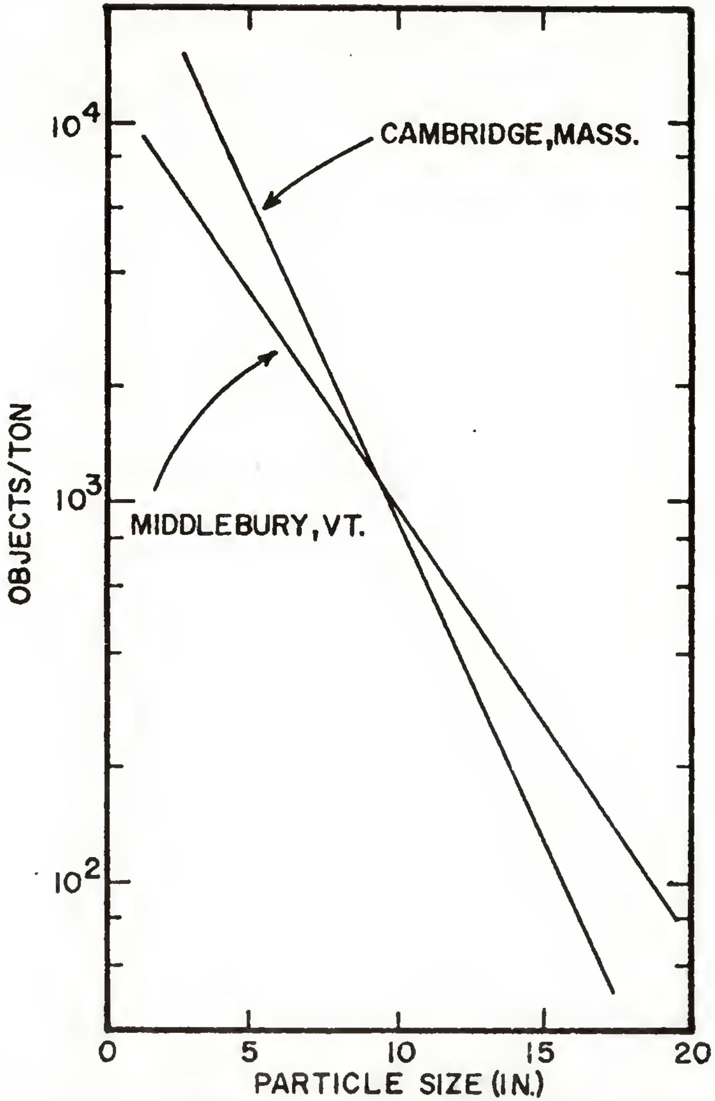

Figure 7. Cumulative number objects per ton of raw refuse which will pass through a square mesh, plotted vs. mesh size [12,54].

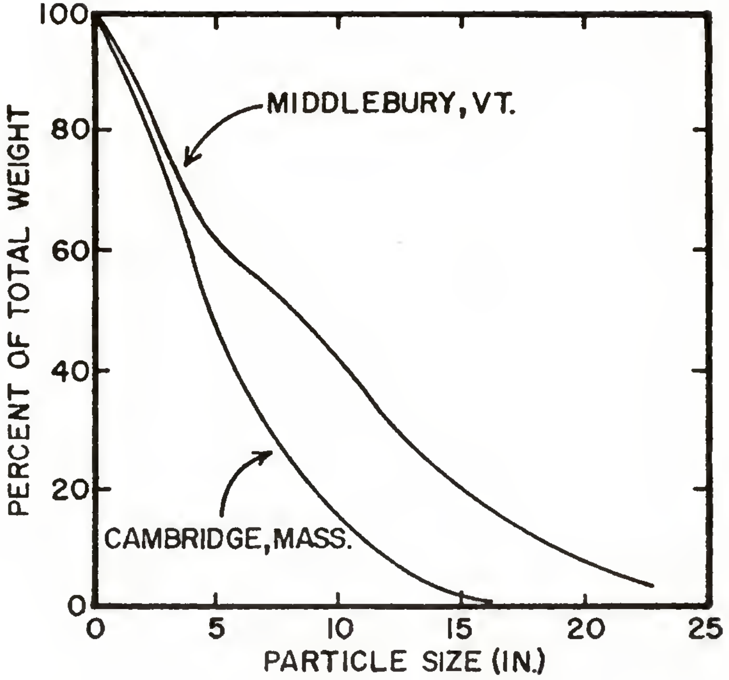

Figure 8. Cumulative weight (percent raw refuse total) of objects which are greater than a square mesh, plotted vs. mesh size [12,54].

varying from 3-1/2 to 6-1/2 in. No other details were provided on this experiment. The results are shown in Figure 9.

Gawalpanchi et al. [21] also reported the particle size gradation of shredded waste at Madison, Wisconsin. They used both sieves and direct measurements of the longer dimension of each particle. A set of thirteen sieves ranging in size from 0.0049 to 2.0 in. were used on previously dried refuse. The 0.132- to 0.220-lb. test samples were accurately weighed, sieved, and the material retained on the sieves accurately weighed. Figure 10 shows the results obtained by measuring the particles of a similar sample by hand and with sieves. Note that the curves become nearly identical for particles less than approximately 1/2 in., so the error in sieve analysis is primarily at the larger particle end. Apparently, for such sizes, particles larger than the mesh in question can work their way through the sieve.

The researchers also explored the method of shaking the screens. Comparative tests indicated that the method of shaking, whether by horizontal or vertical motion, was unimportant. They found that approximately 100 to 125 shakes were sufficient to segregate the material.

The sieve tests were replicated to evaluate sampling and experimental errors. Four 0.176-lb. test samples of dried shredded refuse were randomly collected from a larger gross sample. Each replicate sample was sieved and the size distribution determined (Figure 11). The four distributions indicated the sieve analysis technique was very reproducible.

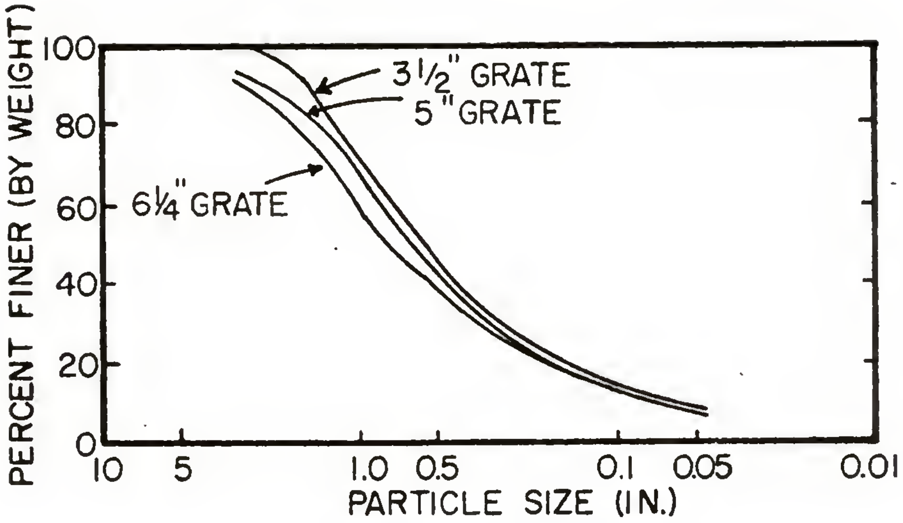

Figure 9. Effect of grate size on particle size distribution at Madison, Wisconsin [19].

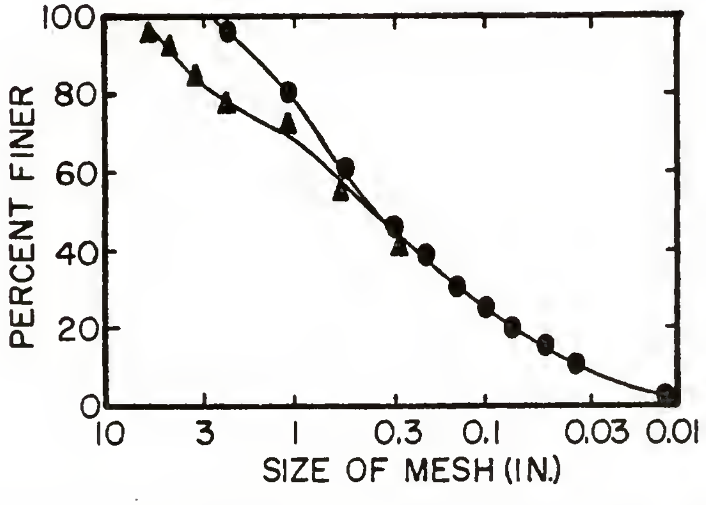

Figure 10. Comparison of sieving and direct particle measurement at Madison, Wisconsin [21].

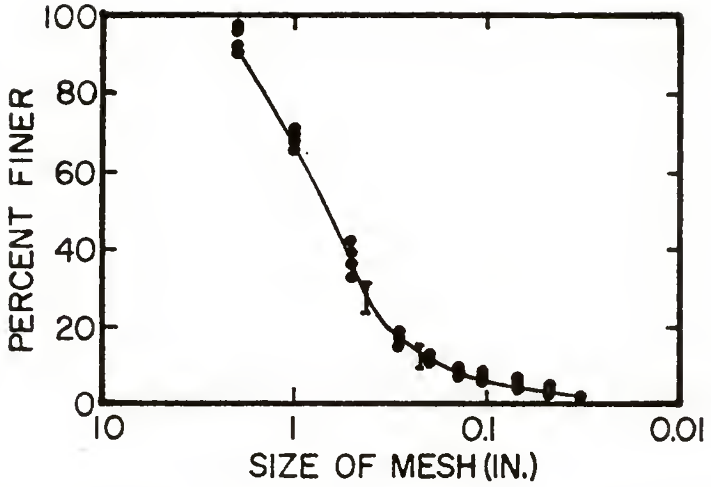

Figure 11. Replicate sieve tests of refuse sample from the Tollemache Mill at Madison, Wisconsin [21].

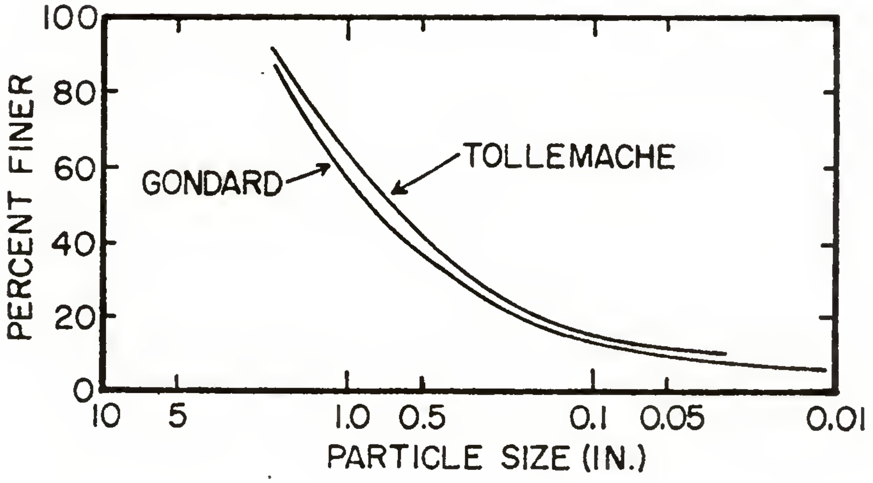

Figure 12. Particle size distributions of waste shredded by the Gondard and Tollemache Mills at Madison, Wisconsin [21].

This and other experiments indicated the distributions tended to diverge at the larger sizes and to overlap at smaller sizes. Therefore, they decided that, rather than working with a complex function describing the entire size distribution, it was sufficient to check for experimental error only at certain portions of the size distribution curve. For example, the quantity of material passing a 1-in. sieve could be compared. If the quantities were found to be unequal, as confirmed by statistical tests, the particle size distribution could be different. The precision of the replicated sieve tests was calculated at the 1, 0.5 and 0.185 in. sizes. The plotted data suggested the experimental error was nearly constant at all points along the curves, and calculations confirmed this finding. The estimated variance due to sampling experimental error was 3.82 percent. The estimated mean percentage of material passing a sieve was accurate within approximately 2 percent.

Gawalpanchi _et_ _al_. [21] also compared the performance of two different types of shredders and evaluated the effect of operational variables, specifically moisture content and hammer wear. Shredded waste was evaluated from the Gondard and Tollemache mills. The Gondard mill was a horizontal shaft hammermill with grates at the bottom of the milling chamber. It was rated at 8 tons per hour and had a 150 horsepower, 1,200 rpm motor. The Tollemache mill was a vertical shaft mill without grates and was rated at 15 tons per hour. Its motor was 200 horsepower and 1,300 rpm. The particle size distributions for both shredders are shown in Figure 12. The distributions were found to be highly skewed with about equal mean particle size. The distributions of all samples tended to converge asymptotically at small particle sizes. The region of greatest difference was found to be the 1-in. size. Statistical t-tests were made to compare the distributions at the 1.0- and 0.185-in. sizes. At these sizes and the 95 percent level of significance, there was no reason to reject the hypothesis that the two shredders produced milled refuse having an equivalent size distribution.

It was noted large amounts of variability existed beyond the experimental errors. This natural variability tended to overshadow any difference arising from physical differences between the mills. It was concluded the variation in refuse composition contributed significantly to the differences in size distributions.

It was further concluded that factors other than moisture content affected the particle sizes since increased moisture content did not always correspond with a finer grind. The correlation coefficient between moisture content and the percent finer than 1-in. mesh was only 0.213. In an effort to avoid variation because of refuse composition, a controlled experiment was run to evaluate the importance of moisture content. A large pile of unprocessed refuse was mixed and divided into three piles. Different quantities of water were sprinkled on two piles so that each of the three piles had different moisture contents (46.3, 66.2 and 91.5 percent moisture on a wet weight basis). Each pile was shredded separately and replicate samples obtained. The particle size distributions (measured in triplicate for each sample) are shown in Figure 13. The graphic presentation very definitely indicates that different distributions resulted from the three different moisture contents. The statistical t-test confirmed the observation.

Tests also were made to determine the importance of hammer wear in shredding refuse. A large amount of wear caused the particles to be less finely ground and the size distribution to be less uniform (Figure 14). The trend was well described by an exponential decay curve with time. Multiple correlation analyses using a linear second order model confirmed hammer wear was a highly significant variable (95 percent confidence limit), but moisture content was not significant at even the 50 percent test level.

Particle Size Distributions of Refuse Components

Several investigators reported refuse components have different particle size distributions not only for raw refuse, but also for shredded waste [12,36,49,50,53,54]. They reported the various components react differently by shredding [53,55]. Patrick [36] was one of the first to recognize different particle size distributions for various raw refuse components. He screened raw refuse utilizing a rotary screen with two sieves (2-in. square and 7-1/8 in. x 5-7/8 in.), thus providing three fractions of sized refuse. The largest

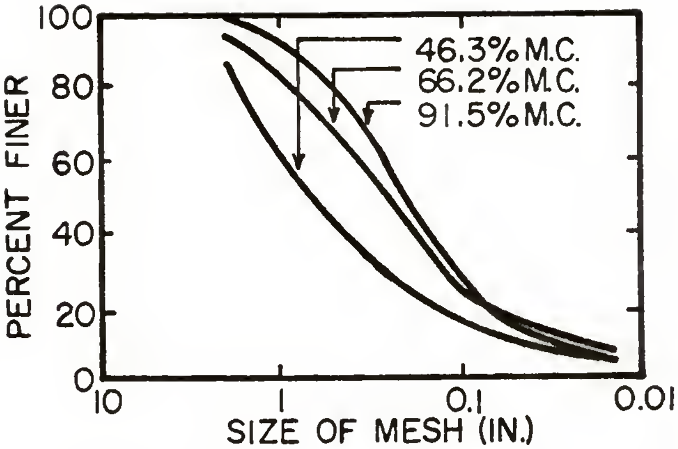

Figure 13. Effect of moisture content on particle size distribution at Madison, Wisconsin [21].

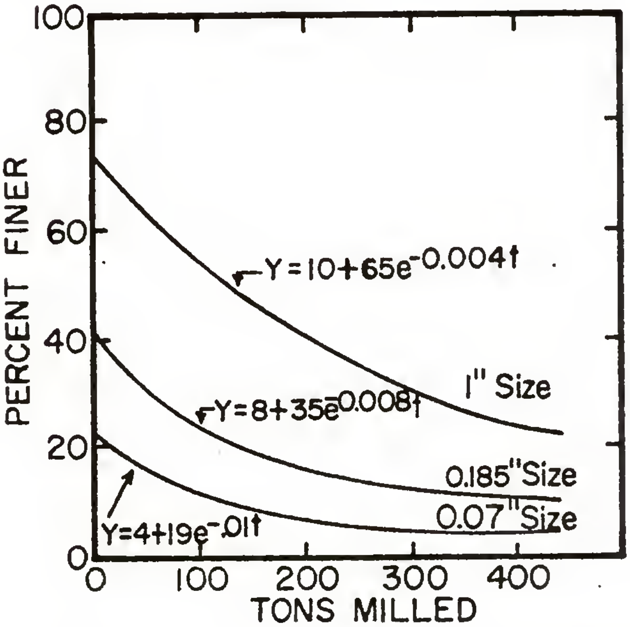

Figure 14. Changes in particle size distribution due to cumulative hammer wear at Madison, Wisconsin [21].

fraction reportedly contained considerable amounts of large textiles and carpeting with the remainder consisting of cartons and large paper. Plastic bottles usually passed through the large screen and were retained on the medium screen.

As previously reported, Winkler and Wilson [12,54] manually measured the size of individual components of raw refuse. Each object was classified into one of nine major component categories and 50 minor categories. Since they found a great many objects were composites of two or more materials, they decided to classify these materials by secondary and tertiary material composition as well, e.g., a clear glass container (primary material) with steel lid (secondary) and paper label (tertiary). Objects which could not be adequately described by the use of the three categories were classified as miscellaneous. They defined an "object" as an item which remained intact after a reasonable amount of mechanical handling.

A special problem presented itself with large plastic and paper bags of waste. Since they assumed a reclamation system will be provided with mechanical devices to open such bags, they decided those bags which could be ripped by grasping two points by hand and giving a good tug were mechanically breakable and thus the contents were considered as separate objects. They found little ambiguity in this criterion. Measurements of flexible objects were somewhat arbitrary, but were taken with the object in an "as-received" condition without either crumbling or straightening the object.

Figures 15 and 16 show the particle size histogram for principal refuse constituents. The height of each column represents the number (or weight) of objects per ton of raw refuse, in 1-in. intervals from 2 to 20 in. The ">20" block at the right of each histogram represents the number (or weight) of objects greater than 20 in. in length. The area of each block represents the same number of pieces (or weight) as an equal area on the histogram.

They concluded each component has different size distributions and interesting patterns emerged. For example, almost half of the total weight of metallics consisted of objects between 3 to 5 in. in length (mostly cans); furthermore, metallic objects made up 40 percent of the total weight of refuse in the 3-to 5-in. size range, as opposed to only 9 percent for refuse of all sizes. Similarly, there was a "bottle peak" in the glass category between 5 to 10 in., and glass objects accounted for 38 percent by weight of the refuse in this range. The researchers noticed very few glass bottles were broken in the collection and dumping process (in a separate study, some 94 percent of the bottles had remained intact). The objects greater than 12 in. in length were predominantly paper products (except the curious peak at 16 to 17 in. in the metal histogram which resulted from a single baby carriage), 67 percent by weight. Of all the paper products, just over 50 percent by weight fell in the over 12-in. range, yet the number of objects here were rather small; only about 1,000 pieces per ton of refuse. Furthermore, they found an

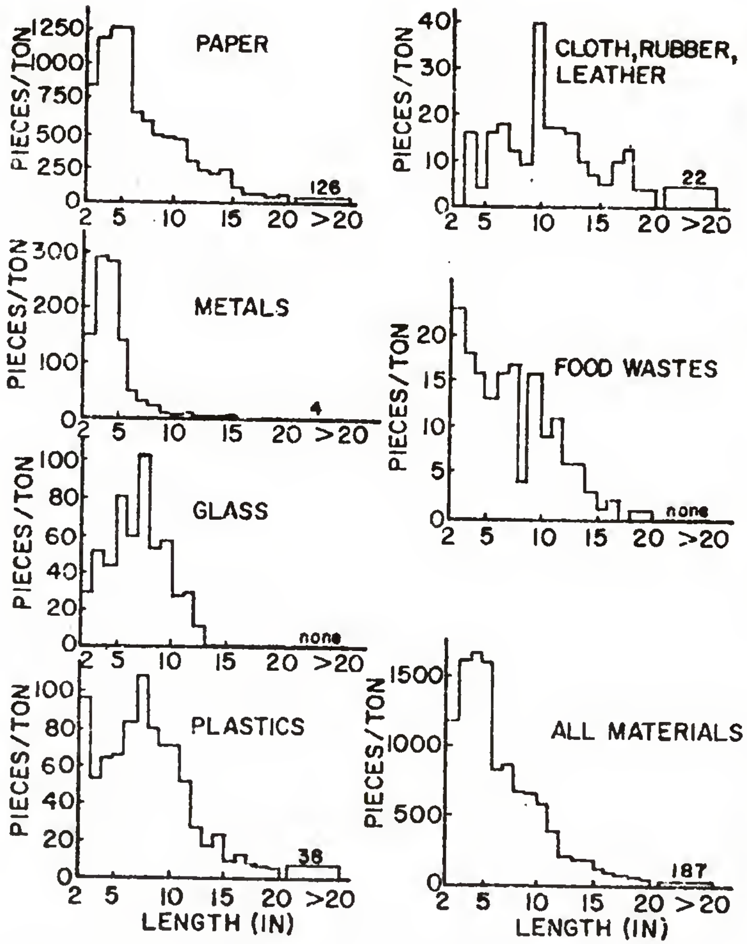

Figure 15. Number of objects per ton of raw refuse vs. length (longest dimension of object) for principal categories of refuse [12,54].

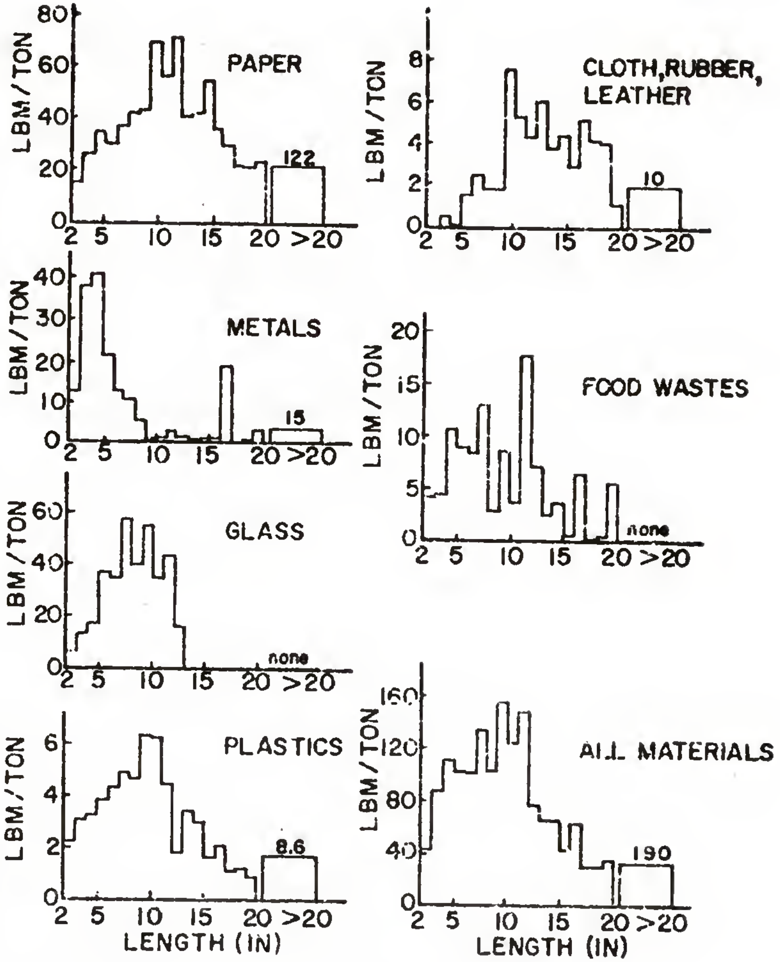

Figure 16. Total weight per ton of raw refuse of objects in given length ranges for principal categories of refuse [12,54].

overwhelming majority of paper products with high recycle value, such as bundles of newsprint and corrugated cartons, fell in this size range.

They concluded sorting by size can be an important process in any automated recovery process. Although sorting alone cannot give a pure product, sorting by size can be used to drastically increase the percentages of sized waste streams of certain components or, to state it differently, to "enrich the ore" from which the products are to be eventually recovered.

Other researchers have also determined the particle size distribution for various components of shredded waste. Stirrup [32,56] reported the distributions of glass, tin cans and wood when these components were fed separately through a 10 ton per hour Jeffrey-Diamond horizontal shaft hammermill. The results are provided in Figure 17. The details of the sieve analysis were not provided. Stirrup mentioned the glass particles would have been reduced further if they had been mixed with refuse and thus retained in the machine for a longer period of time. He noted pieces of shredded wood were as large as 8 in. x 1-1/2 in.

Fess [49] reported the particle size distributions for various components of shredded waste. He visually estimated the percent weight of the major components of each fraction size of several samples. His results have been adjusted and are presented in Figures 17 and 18. The composite samples are the same as presented earlier.

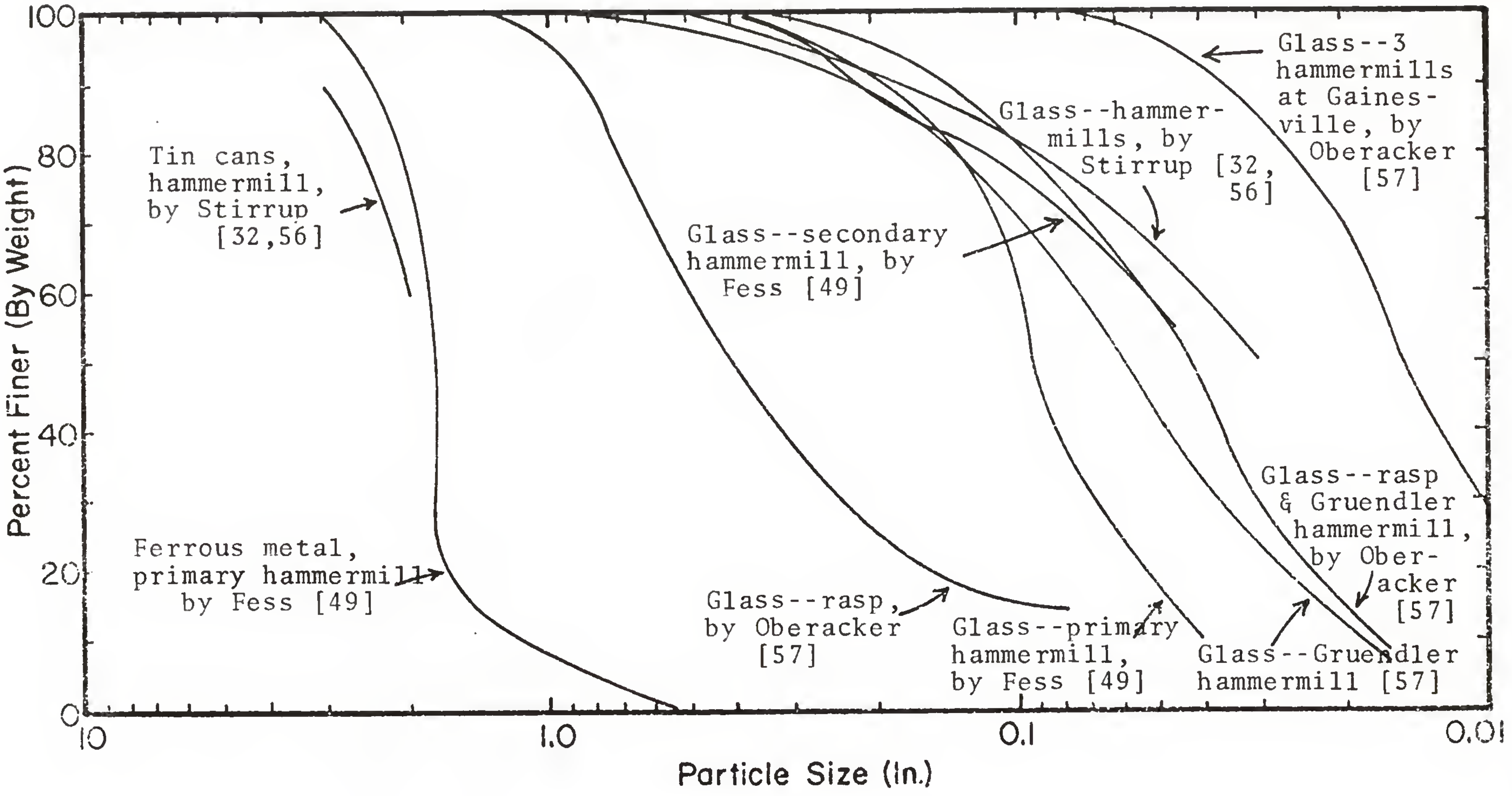

Figure 17. Particle size distributions of metal and glass waste.

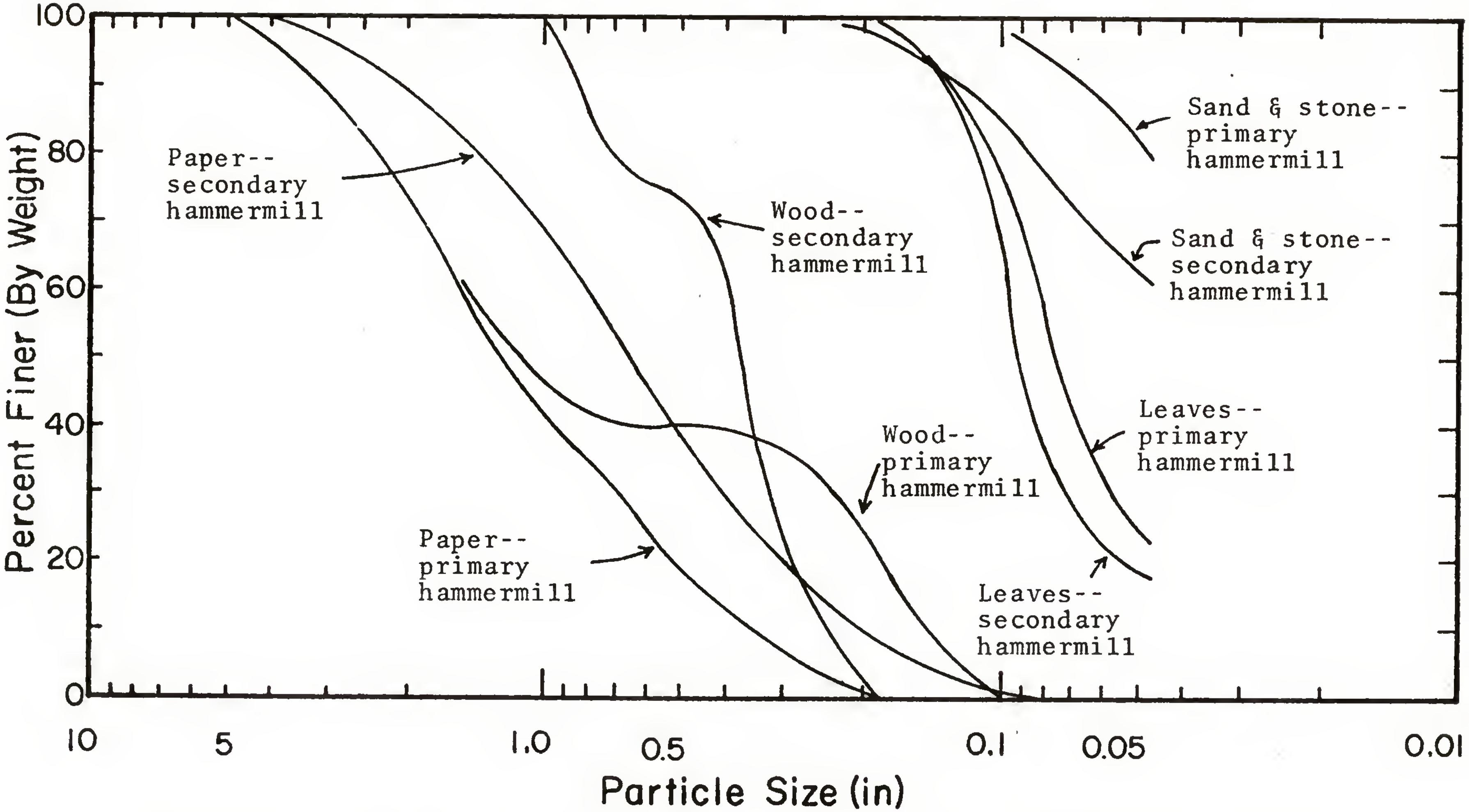

Figure 18. Particle size distributions of miscellaneous components of waste. By Fess [49].

Fess [50] collaborated with the author in analyzing and evaluating the particle size distributions of selected components (paper, cardboard and glass) of shredded waste samples used early in this research. The distributions of the components were determined by manually classifying each sieve fraction into its various components. For example, the 2-to 4-in. fraction was subdivided by hand into 13 categories (e.g., paper, cardboard, glass, ferrous metal, non-ferrous metal, plastic, etc.). This was done for each fraction. The sorted components were weighed and the subsequent distributions obtained. It was found that sorting the very fine material (less than 3/8 in.) was a time-consuming effort (1 to 5 hours). His procedure was to separate the easily distinguished and separable items from the fines, i.e., ferrous by magnet, etc., and then estimate by partitioning the proportion of the remaining items (this technique was altered later in this research). Estimates were independently made by two or three individuals and averaged.

The median particle size of each component of each sample was calculated and the population medians estimated. The t-test was used to determine whether the medians of the secondary shredded components were significantly less than the medians of the primary shredded components (95 percent confidence level). The results are provided in Table 3.

Fess concluded that of the three solid waste components, the cardboard fraction showed a less significant difference between the primary and the secondary samples.

Table 3

Parameters of Selected Components of Shredded Waste [50]

Type of Sample	Number of Samples	Paper		Cardboard		Glass	
		Median (in.)	Standard Deviation (in.)	Median (in.)	Standard Deviation (in.)	Median (in.)	Standard Deviation (in.)
Primary	4	1.016	0.377	2.778	1.295	0.126	0.0355
Secondary	7	0.431	0.165	1.432	0.643	0.0598	0.0145
$t_{calculated}$		2.95		1.945		3.55	
$t_{\alpha=0.05}$		2.31		2.303		2.315	
Conclusion:		different medians		same medians		different medians	

Fess also found the distributions of the paper components were highly skewed to the right when plotted on arithmetic graph paper. When the cumulative finer distributions were plotted on semi-log paper, he found that the curves were definitely "S" shaped; a straight line was obtained when plotted on log-normal graph paper. Similar results were obtained for the cardboard and glass components. Fess also evaluated the "goodness of fit" using the Kolmogorov-Smirnov test for maximum deviations.

Oberaker and Schomaker [57] analyzed the particle size distribution of glass from different types of shredded waste. Three of the samples were obtained from the Johnson City compost plant (sample Nos. 1 to 3) and the other from the Gainesville compost plant (sample No. 4). A description of the samples is provided in Table 4.

The glass was separated from the compost using liquid gravity separation techniques and successive acid treatment. The samples were then washed and dried. The sieve analysis was performed in accordance with the procedures outlined in ASTM D 422-63 [58]. A mechanical sieve shaker was used and the samples sieved for five minutes. The results are shown in Figure 17. The shredders at Gainesville produced the finest glass particles, while the rasp at Johnson City produced the coarsest glass.

Several other researchers have reported the particle size of various components of shredded waste. The Hazemag Novorator hammermill is reportedly capable of shredding glass

Table 4

Parameters of Glass Component from Shredded Waste [57]

Sample Number		Net Sample Weight (lbs.)	Glass Weight (lbs.)	Percent Glass	Maximum Particle Size (in.)	Median Particle Size (in.)
1	Rasp	24.2	1.58	13.6	2-1/8	0.472
2	Gruendler Hammermill	24.0	2.58	22.4	1-1/4	0.063
3	Rasp & Gruendler	24.3	1.43	12.2	3/8	0.051
4	2 Williams & a vertical shaft hammermill	0.79	0.064	12.4	5/64	0.016

and porcelain, so that only 1.6 percent remained on a 5-mm screen [59]. Other researchers also concluded that glass, porcelain and stone are reduced to very small particles by hammermills [48,50,53,55,60] or high speed Roto-Shredders [61].

Elastic or fibrous material, such as rubber, nylon, textiles or leather, are not efficiently shredded and frequently pass through shredders virtually unaffected [49,50, 55,60-64]. Rugs may come out of shredders in pieces up to a square foot or more in size. Leutelt [55] easily separated these items from shredded waste utilizing screens with 0.984- and 3.150-in. mesh. Steel and aluminum cans were found to be mangled and rolled into balls [53,61,65]. Large pieces of wood were not shredded in small mills [53] but were ground to finger size in large shredders [65]. Large plastic bottles were mangled but not substantially torn or shredded [53,62]. Sheet plastic tended to come out in long pieces [53].

Large particles resulted when special hammermills for large metal objects and bulky objects were used. The typical particle size of shredded metal from automobile shredders is 2 by 4 in. [66]. The Hazemag Impact Crusher used at Buffalo, New York, to shred bulky materials provided the following percentages of crushed particles for shredded metals, measured according to the greatest dimension [63].

Over 12 in. -- 93 percent
4 to 12 in. -- 6 percent
Under 4 in. -- 1 percent

This machine had a horizontal rotor and suspended impact arms; it had no grates. Sheet metal from appliances were reported torn off in large pieces and came through the crusher as crumbled sheets from 1/2 to 12 sq. ft. in area. The larger sheets came through in unpredictable random dimensions, e.g., 4 by 3 ft., 6 by 2 ft., etc. It was necessary to recycle the heavier gauge metals (e.g., hot water heaters) so these particles were sufficiently reduced such that one dimension was approximately 8 in. Carpets and tires were observed to frequently pass through the crusher virtually unaffected.

Refuse Composition Classification Techniques

In order to determine the particle size distributions of various compositions of refuse, the components of the refuse should be classified into categories. The sample must be physically separated so that each particle is defined to some mutually exclusive category, e.g., paper, food, plastic, metal, etc. Determining the physical and quantitative composition of solid waste is a necessity for solid waste systems, e.g., incineration, composting, resource recovery. Thus, many researchers in the past have classified refuse [10-12, 14-16, 19,22,32,49-51,53,54,56,67-72], almost exclusively for raw refuse. Separation techniques have even been recommended by APWA [4] for use in chemical analysis.

One of the initial decisions in classifying refuse is to determine the subdivisions of the material. A classification scheme should have the following properties [22]:

(1) categories which lend well to visual recognition and hand separation;

(2) categories composed of materials of similar nature; and

(3) categories selected to permit relatively direct comparison with previous studies and existing data.

Unfortunately, the individual requirements of a classification scheme are often contradictory. A research may require narrowly defined categories. When hand separation is utilized, however, such a requirement may multiply the costs and problems, thus prohibiting the scheme.

The literature review indicated that, although no standard set of categories for refuse constituents has yet been adopted, many researchers have used similar categories. The overwhelming choices appear to be:

(1) paper;
(2) glass and ceramics;
(3) metals;
(4) plastics, leather and rubber;
(5) textiles;
(6) wood;
(7) food;
(8) garden and yard waste; and
(9) ashes, dirt, bricks and stone.

Many researchers have subdivided several categories into additional units, e.g., metals have been replaced with ferrous and non-ferrous metals, plastics have been made a separate category, and paper has been divided into different types of paper. Many classification schemes have a "miscellaneous" category.

The classification scheme proposed above has been recommended by personnel of the federal solid waste program [15, 22]. They felt that it essentially incorporated mutually exclusive components, each of which was similar in composition. In addition, the personnel felt the scheme was adaptable to the analysis of solid waste received at any disposal facility or generated at any source. They estimated four men could separate and weigh approximately 2,000 lbs. of raw refuse in an eight-hour day utilizing this scheme.

The selection of a classification system does not guarantee the accuracy of the results [12,22,55]. Frequently subjective decisions are required with inherent ambiguities. The technician who, for example, encounters a glass jar filled with food wastes, a toy constructed of both wood and plastic, or a residue of unrecognizable fines, is faced with a number of critical decisions. As with everything else, an excellent classification scheme with adequately trained personnel is required, but the technician's best judgment is the final arbiter in these matters. If the decisions are consistent, then results will be comparable and reproducible, a primary requirement for any classification plan.

Any proposed classification scheme presents several potential ambiguities which must be solved prior to separation. These problem areas are:

(1) Items constructed of several materials. Winkler and Wilson [12,54] felt they overcame these problems by adding secondary and tertiary classifications.[1] Winkler and Wilson emptied boxes and bags prior to analysis to reduce the bi-composition problem. The investigators at Sulfur Springs, Texas, emptied the contents from bottles, cans, boxes and bags, as well as removed aluminum tops from bottles [53].

(2) Differentiation of wood in "Garden and Yard Waste" from "Wood." Fess [50] considered a tree branch (less than 1/4 in. in diameter) as "Garden and Yard Waste," while investigators at the Gainesville compost plant [10,20,73] used 1 in. as the critical diameter.

(3) Classification of Fines. Winkler and Wilson [12,54] did not classify objects less than 1 in. in diameter, but instead categorized them as "Miscellaneous and Uncategorized." This represented 15 to 20 percent of the total waste. Higginson [7] and Stirrup [56] had difficulties in classifying fines passing 1/2-in. mesh screen; they provided a separate category for the fines. Britton [15] also used an additional category for the fines. In defining the end-point of the fines, he used two screens (1 in. and 1/2 in. openings). He found the manpower required to separate a 100-lb. sample to fines which would pass a 1-in. screen ranged from one to five man-hours (averaging 2.25 man-hours). Separation to this point left an average of 5.6 percent fines. The additional

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[1] This appears to complicate the problem for it requires the addition of many more categories.

manpower requirement for continuous separation to the point the fines would pass a 1/2-in. screen ranged from 0.33 to 2.75 man-hours, and averaged 0.79 man-hours. For this additional labor, the fines were only reduced to 3.8 percent of the original sample.

Fess [50] expended considerable time in classifying the fines from shredded waste. About one to five hours were required to classify the screen fractions less than 3/8 in. from samples with a total weight of 2,000 grams. He found it necessary to separate easily distinguishable and separable items (e.g., ferrous metals by magnets), and then estimate the other components.

Oberaker and Schomaker [57] utilized liquid gravity and acid treatment separation techniques to remove glass from compost.

(4) Defining Ferrous and Non-Ferrous metals. Magnets were used by many researchers [10,11,20,50,73] to define ferrous metals.

(5) Salvageable vs. Unsalvageable Paper. This category was arbitrarily defined by researchers at Gainesville as large pieces (over 12 in.) of relatively clean and dry paper [10,11,20,73].

(6) Cardboard vs. Other Paper. Cardboard was arbitrarily defined as corrugated and other thick paper by researchers at the Gainesville compost plant [10,11,20,50,73].

(7) Rock and Gravel vs. Sand and Dust. Fess [50] defined rock and gravel as particles greater than the No. 8

screen; all other particles were assumed to be sand and gravel.

(8) Synthetic Clothing. Woven synthetics were considered as textiles instead of plastics by Niessen and Chansky [68].

Moisture introduces potential errors. The majority of researchers conducting refuse composition studies have reported their results on a wet weight basis [67]. In order to accurately compare the results from several studies, it is important the moisture content of each study be specified. Certain materials are hygroscopic and thus moisture transfers can occur between one constituent to another (such as paper coming in contact with wet food wastes), or certain components can absorb rain when the refuse container lids are left off. Several researchers have attempted to solve the problem by either drying the samples or reporting the results on a dry weight basis. Britton [15] mentioned the separation data of his studies were recorded on a wet weight basis, but during the separation study the moisture content of each component was determined and the components were later adjusted to a dry weight basis.

Commercial Application of Screens

The sizing of material is not a new industrial process. It has been used for ages, especially in the mineral-oriented fields. It has even been used for some time with respect to solid waste. A combination of shredders and screens has been found to constitute a unit separation process because one or more of the refuse constituents tend to grind more easily than another, thus producing various sizes of fractions [32, 50,74]. For example, during shredding, brittle materials (e.g., glass) usually end up in smaller fragments than paper, while metals, textiles, plastics and heavy items end up larger. This also is true when screens are used in conjunction with digestion, where the biological action attacks and reduces the paper and food fractions, while the metals, glass and plastics remain untouched. Screens have been proposed for use with raw refuse to remove the smaller particle-size fractions of solid waste which are too small to be feasibly reclaimed and interfere with the reclamation of the larger particle fractions [15,25,75].

Screening is relatively simple and inexpensive with very low power requirements. The only significant maintenance cost has been the screen cloth replacement. Screens are also very versatile and can be used as stationary or moving, flat, inclined, rectangular or circular. The screen movement may be brought about by shaking, rotating, or vibrating. Screen openings vary from several inches or more to fine screens with openings of 0.0015 in. in diameter or finer. Coarse grizzly screens have even been constructed with railroad tracks. The screen openings may be round, square, rectangular or slotted, and the wires may be round, flat, and wedge-shaped [74].

The greatest use of screens with solid waste has been at composting plants in conjunction with a combination of rotary and vibrating screens [32,76-80]. They were provided for two main purposes: (1) to remove the fines (sand, earth, and ashes) from the raw refuse prior to shredding and digesting; and (2) to remove contaminants and oversize items (rubber, leather, plastic, glass, metals) from the finished compost. They also have been used in intermediate processes to remove oversize items immediately after shredding and prior to digestion [79]. One investigator mentioned the use of a vibrating screen at the front of a composting plant to remove bulky items [81].

Screens have been used ahead of shredders without subsequent composting. Stirrup [56] mentioned the City of Salford, Great Britain, provided two large rotary screens ahead of their transfer station to extract dust and fine cinders. The screen plates were provided with 1-1/2 in. long and 3/8 in. wide slots. Patrick [36] felt that: (1) screens can be used to separate undesirable items (ashes, dust, bulky items) from refuse prior to shredding; (2) large screen openings can be used to remove most of the rejects and small screens can be used to remove fines; (3) the hammer life of shredders can be lengthened considerably if the ashes and other fines are removed (one location reported 50 percent increase of hammer life when screens were used to remove 30 percent ash); and (4) the screen could serve the dual purpose of a screen and a feeder, thus eliminating the need of one conveyor.

Screens are used in many reclamation systems including the wet pulping process at Franklin, Ohio [82], and the Bureau of Mines incinerator ash recovery system at College Park, Maryland [83]. They may be provided directly ahead of air classifiers in order to size shredded waste for further processing [32,74,84].

Several rotating drum shredders (which are common in Europe) are also provided with screens [36]. The machines shred waste utilizing the principle of attrition. Water in controlled quantities is added to the refuse to reduce the fiber strength of materials, such as paper, food and garden waste, though it has little effect on reducing the size of metals, plastics, wood, textiles, etc. Thus a screen can be used to separate the two fractions of wastes. The shredding is achieved by the churning effect of the rotating drum with the amount of reduction being a function of rotation speed and retention time within the drum.

The Fermascreen is an octagon or hexagon shaped rotating drum which performs the multiple duty of mixer, screen, and shredder in one unit. The drum rotates at 1.6 rpm and the process is completed in approximately 2-1/2 hours. Since the shredded material will not pass through the screen until it is reduced to the required size, a uniform product is obtained. Rejects may be discharged at the same time as the shredded material or retained in the drum for later discharge, whichever is convenient [36].

The Seerdrum, another rotating drum, is 8 ft. in diameter, 29 ft. long and rotates at 11-1/2 rpm. The first 12 ft. of the drum consist of a solid plate and shredding is effected by the combined churning and shearing action of the deflection plates. The next section of the drum has 2-in. diameter circular perforations and the shredded material falls through these holes into an annular space between the drum and the outer casing. A helix on the external surface of the drum feeds the shredded product on the discharge conveyor. Constituents of the refuse which do not break down, e.g., plastics, metals, and rubber, pass out at the end of the drum and are disposed [36].

The Volund shredder, although basically a wet rotation process machine, includes a further shredding element in the shape of beater arms, or paddles, on a central shaft rotating in the opposite direction to the drum. The drum itself consists of screen plates. The first section normally has 7/8 to 1-1/2 in. diameter holes to remove dust and other small materials which collect in the hopper below. Shredding takes place mainly in the second section, where the contra-rotating blades break up the material as it is tumbled in the drum. The shredded material falls through 2-in. circular perforations in the main section of the drum into a hopper. Rejects pass out at the end into a third hopper [36].

The Dano rotating composting drum at Aberdeen, England, had two screens [85]. The inner screen has 4-in. diameter holes and the outer screen has 1-1/2-in. diameter holes.

This allows the composted material to be separated into three fractions: less than 1-1/2 in. (typically paper, cardboard, and organics), 1-1/2 to 4 in. (typically metal, stone, rubber, and plastic), and greater than 4 in. (bulky and textile items).

Other types of shredders also incorporate some particle sizing devices [32]. The Dorr-Oliver rasp, for example, utilizes a perforated floor through which the refuse must pass and most hammermills utilize grates or bars which also act as a sizing device.

Particle Size Requirements for Various Industrial Processes

The literature review indicates a wide range of recommendations concerning the particle size requirements of processed refuse for various industrial processes. Obviously, this is because essentially no research has been undertaken to correlate the efficiency of these processes with refuse particle size. In addition, many of the specifications have been somewhat arbitrary and unspecific.

Most of the refuse shredded today is destined for mill-fills. Oates [86] reported shredded refuse with a maximum particle size of less than 3 to 4 in. was found acceptable for mill-fills. However, he suggested the refuse be shredded to a particle size of 1 to 2 in. when the mill-fill is near homes. Herb [87] recommended the maximum size of shredded waste be in the order of 6 to 10 in. to eliminate the need for daily top soil. Smith [88] suggested the particle size for waste destined for mill-fills be shredded sufficiently so that 90 percent is less than 4 to 6 in.

The hammermill shredders at Slough, England, were specified so that no more than 5 percent of the shredder waste was retained on a 3-in. screen [89]. The shredded waste was then mill-filled. The hammermills at Cringle Dock in London were specific to insure 80 percent of the material passed a 1.75-in. screen and the remaining measured no more than 6 in. [40]. The hammermill at the Newham Dock in London shredded the refuse so that 90 percent passed a 2-in. screen and 25 percent was below 1/2 in. [38,39]. The processed refuse from both of these docks was transported by barge to a mill-fill. Most rotating drum-type shredders in Europe produce processed refuse (destined for mill-fills) in which 100 percent passes a 1-to 2-in. screen [36]. The vertical shaft hammermill at Pompano Beach, Florida, reportedly shreds the refuse to a 3-in. nominal particle size prior to mill-filling [90].

In the case of suspension furnace firing, the particle size is very important and specifications are usually quite detailed. For example, the specifications for the St. Louis, Missouri, installation (which shreds waste for tangential burning in a power plant furnace) require 95 percent of the material with a 1.5 in. nominal size, while 100 percent must pass a 5-in. screen [91,92]. A pneumatic pipeline is used to convey the shredded refuse directly into the furnace, where the refuse is burned in suspension with pulverized coal. Regan [93] also felt particle size is important for suspension burning, and has recommended refuse be reduced to a maximum size of a 2-in. square before being conveyed and burned in the furnaces.

The particle size requirements for waste used with air classifiers vary. The recycling system at San Diego requires the shredded waste be reduced to a "five-inch minus particle size" prior to the cyclone air classifier [94].

With respect to composting, various investigators [87, 95,96] have recommended the particle size of raw refuse be shredded to the order of 1 in. prior to digestion. The maximum particle size of finished compost for agricultural purposes has been recommended at 1 in. [97], while the maximum particle size for compost used in greenhouses and nurseries is recommended at 1/8 to 3/8 in. [87,89]. Screens are usually provided after shredders and digesters at composting plants to remove oversize items which are not reduced.

Experimental Methods and Equipment

Introduction

Many methods were noted for determining the particle size of a wide array of materials; each method usually had several variations. In making a decision on which techniques and variations to use, the first consideration was the purpose of the analysis, so that a method could be provided which measured the property to be controlled. Since the ultimate use of processed solid waste is still in its infancy, and its use can vary considerably (e.g., wet vs. dry, chemical vs. biological reactions, etc.), it is impossible to predict with reasonable accuracy which properties of solid waste particles will be most important to the industrial sector in the future. Therefore, various measuring techniques may be appropriate. At any rate, a dry method is probably preferred, because most solid waste processed today operates with dry or semi-dry material. With respect to the future, for energy recovery, a dry material is very likely to be required.

In order to decide which method to use, the accuracy and reproducibility of the method must be considered. Unfortunately, very little information is available on this subject. The ASTM standards do not mention the accuracy of specific procedures; in fact, they state no comments could be made on precision at this time because of insufficient data [27,28]. Only one reference was found which determined the experimental error for sieving refuse; this was done for very small samples (80 grams) and only for one type of waste (shredded). Also, it was replicated only four times and the experimental error included sampling error from the gross sample. This work was done by Gawalpanchi *et al*. [21] who used thirteen sieves from 0.0049 to 2 in. They found the experimental error was nearly constant at all points along the distribution curve. The estimated variance due to sampling and experimental error was found to be 3.82 percent. The estimated mean percentage of material passing a sieve was accurate to within 2 percent.

Gawalpanchi _et al_. [21] compared the sieve distributions to distributions obtained when the larger particles (larger than about 1/4 in.) were directly measured by a rule. The longer dimension of the particle was considered its size when the latter method was used. The sieving method was consistently less than the direct measurement for the large particles, but the curves became almost identical for particles less than approximately 1/2 in. (see Figure 7 on page 54).[1] Their findings were the opposite of Winkler and Wilson [12,54] who theorized the vibrating screen would pass fewer objects than direct measurement.

Oberaker [47,48] recognized the necessity of having a large screen area to give increased accuracy and reproducibility. He recommended the screens have surface areas of 100 to 150 sq. in., considerably greater than the 28-sq. in. screens he used with his 14-gram samples.

ASTM Designations E 276 [27] and E 389 [28] state the selection of the sample, loading of the sieves, the sieves, and all weighings influence the reproducibility and accuracy of screening. Particle wear was found to be insignificant. Brittleness or hardness of the material and the mode of operation of the mechanical shakers only slightly influenced the results. The size and shape of the particles significantly influenced the probability of passing through a sieve aperture when the particle sizes were close. The amount of screening time also was important.

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[1] The major reason for this difference must be that sieving depends upon the smallest two dimensions of a particle, while Gawalpanchi _et al_. used the largest dimension. In addition, apparently the vibrating action of the sieve was sufficient to pass some of the larger particles.

Based on the experience of various investigators, it was concluded the method for determining the particle size of solid waste would be with sieves. The only exception to sieving was for measuring the larger particles. The experiences of Winkler and Wilson [12,54] and Gawalpanchi *et al.* [21] of measuring large particles by hand appeared to be appropriate here. The sizing of large particles by hand is also supported by ASTM. Their Designation E 389 [28] for metal-bearing ores, recommended the 2-in. or larger particles be tested by hand to see if they could pass through the mesh. It was noted that for particles greater than 2 in., the probability of them falling through the sieve is related to their shapes.

Equipment

In the development of any standard method, it is important the equipment utilized conform to some standard or specifications, such as ASTM. In addition, the equipment should readily be available so that other researchers can duplicate the procedures. Thus, in the selection of equipment for this research, readily available equipment was used whenever possible.

Regardless of the equipment used, it is important that it be capable of handling a variety of wastes (raw and different types of shredded), with particles of different composition and size. The equipment chosen must be able to handle very fine materials to large items over 12 in., without any problems and damage to the particles. The literature review indicated it was possible for screens to be exclusively used for shredded waste samples, but a combination of sieving and direct measurement was necessary for the raw waste samples. This was because large screens are not readily available, and the vibrating screen action might damage these larger particles.

Originally, it was felt a rotary screen would be desirable, basically because the rotary action would gently rotate the particles at various angles, thus increasing the probability that even the long particles would pass through the sieve. Secondly, it appeared rotary screens would have a high degree of self-cleaning ability. Unfortunately, laboratory rotary screens are not readily available and it was not desirable or recommended to construct one. Other types of screens were reviewed instead.

The air-jet system utilized by Oberaker [47] appeared somewhat cumbersome and inaccurate. In this system air-jets were directed toward stationary screens, agitating the refuse particles so they would pass through the sieve. The method appeared to encourage the loss of a good deal of fines.

The samples could be sieved using the hand-sieving or the mechanical sieve shaker method. In hand-sieving, usually the tests were made on one sieve at a time. For very small sieves, it may be possible to use a nest of sieves. Due to large sample sizes required for solid waste, it is obvious hand-sieving is not an ideal method. Mechanical sieve shakers are used in practically all laboratories where frequent tests are made. They not only eliminate much tedious hand labor, but, when properly used, they produce more consistent results. There are several general types of mechanical sieve shakers, some designed to simulate hand-sieving, others using a tapping action [3]. The standard mechanically operated sieve shaker (Tyler Ro-Tap or equivalent) imparts a uniform rotating and tapping motion to a nest of 8-in. diameter sieves [34]. The sieve shaker produces 140 to 160 raps per minute and 280 to 320 rotating motions per minute.

Gawalpanchi *et al*. [21] ran comparative tests on the method of shaking the sieves for shredded refuse and found the shaking motion was unimportant. ASTM [28] concurred, stating the mode of operation of mechanical shakers only slightly influenced the sieving results. Higginson [18] and Leutelt [55] felt the motion was important and recommended one with a large amplitude and a low frequency. Higginson used a screen with 200 cycles per minute and a 6-in. horizontal amplitude; Lambe [23] also felt a horizontal motion was more efficient than a vertical. Leutelt recommended a cascade screening motion.

In order to obtain a high degree of accuracy and reproducibility for refuse (especially raw refuse), it is necessary to sieve large size test samples. This requires screens with large surface areas. The ASTM Manual on Test Sieving Methods [3] recommended the standard 8-in. diameter screen (which is 2 in. deep) be used for samples where the largest particles do not exceed 1 in. For larger sized particles, it recommended larger diameter frames (e.g., 10 to 18 in. diameter). Large screens are also recommended by ASTM Designation C 136 [33] for aggregate with large particles (16-in. diameter or larger screens).

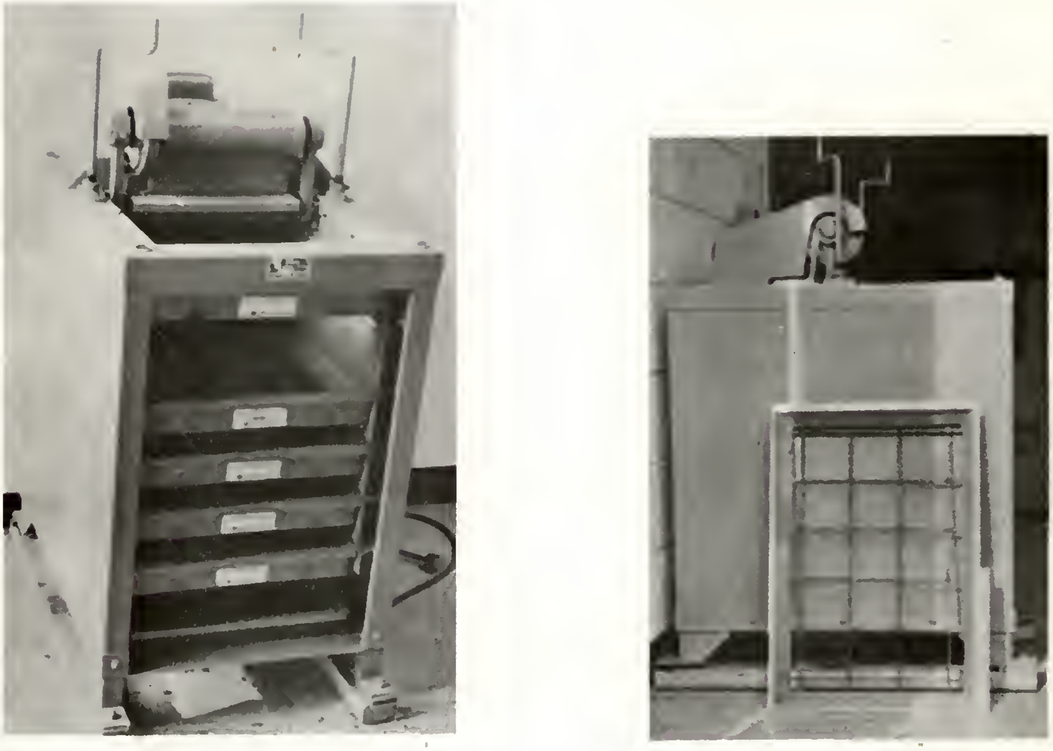
The selection of a set of sieves for a given test depends on the material to be tested [23]; larger openings are required in the top sieve for coarser material. Various screens have been used by previous investigators working with solid waste. The typical size of screen openings for shredded waste ranged from 1/16 in. to several inches. Through previous experience with Fess [49], it was felt a 4-in. screen would be necessary for shredded waste and a screen opening several times greater would be required for raw refuse.

The preliminary investigation by Fess [49] using the Gilson screen was very valuable and the equipment appeared to be promising. The equipment and method worked reasonably well and, with slight modifications, appeared to be applicable for raw and shredded solid waste. Not only did the screens have a large surface area, but they were available with openings up to 4 in. For larger sizes, either special screens would have to be constructed or each particle measured directly by hand. The Gilson screen trays are 14-1/2 in. x 22-3/4 in. x 2-5/8 in. with a screening area

6.5 times greater than the standard 8-in. diameter sieve. Thus, at the same unit loading, the Gilson screen should be able to take a sample 6.5 times greater in size than the test samples used by the standard sieves. This should increase the accuracy and reproducibility accordingly.

The selection of a set of sieves also is important for accuracy and reproducibility, because less interpolation is required with a greater number of sieves. In addition, the extra sieves may prevent overloading of the lower screens. Most of the previous investigators used only a few sieves; several used 5 to 8, while one used as many as 13. ASTM [23] has recommended a nest of sieves for soil grain size analysis in which each sieve has an opening of approximately one-half that of the coarser sieve above. This spacing was found adequate in preliminary work with Fess [49], with one exception. The screens between No. 4 and 1 in. were overloaded, and because of this, intermediate screens were added.

Gilson mechanical testing screens were purchased for this research from Soil Test, Inc. (Model No. CL-325), with ten screens. Two photographs of the machine are provided in Figure 19. The machine held up to six screen trays and the dust pan at the same time. The screens were stacked vertically, 4 in. apart, thus allowing a 1-3/8 in. clear space between them for observation of the operation. The screening agitation was in the vertical direction with a 7/16 in. oscillation at 10 cycles per second. The machine was designed to accommodate up to 1 cu. ft. of sample, primarily for



Front view showing top opening and spacing between screens.

Side view with 4-in. screen leaning against the machine.

Figure 19. Photographs of the Gilson mechanical testing screen.

materials in the No. 4 to 4-in. coarse range. All of the screens were constructed with precision to meet the specifications of ASTM. Further equipment details and costs can be found in Appendix D. Table 5 provides data describing these screens.

Table 5

Gilson Screen Data Used in Research

Screen Size	Aperture Opening (in.)	Class Boundaries (in.)	Class Width (in.)	Class Midpoint (in.)
16	16.00			
		8.00-16.00	8.00	12.00
8	8.00			
		4.00-8.00	4.00	6.00
4	4.00			
		2.00-4.00	2.00	3.00
2	2.00			
		1.00-2.00	1.00	1.50
1	1.00			
		0.750-1.00	0.250	0.875
3/4	0.750			
		0.500-0.750	0.250	0.625
1/2	0.500			
		0.375-0.500	0.125	0.4375
3/8	0.375			
		0.1875-0.375	0.1875	0.2813
No. 4	0.1875			
		0.0937-0.1875	0.0938	0.1406
No. 8	0.0937			
		0.0469-0.0937	0.0468	0.0703
No. 16	0.0469			
		0.0234-0.0469	0.0235	0.0352
No. 30	0.0234			
		0-0.0234	0.0234	0.0117
Pan	0			

The screen openings in each sieve were square, except for a few of the openings in the larger screens. These had some holes which were not square due to the impossibility of constructing sieve trays of a given dimension while maintaining the exact ratio of the sieve holes. The screens and their partial openings are provided in Table 6.

Table 6

Size of Partial Openings in the Gilson Screens

Screen Size (in.)	Size of Partial Openings (in.)
4	1 x 4 and 3/4 x 4
2	3/4 x 2 and 5/8 x 2
1	5/8 x 1
3/4	1/4 x 3/4

Since the 4-in. screens were the largest screens available with the Gilson, another measuring method was necessary for larger particles. Two sieves were made out of cardboard, one with an opening of 8 in. by 8 in. and the other 16 in. square. Each large particle was then tested by hand to see if it could pass through the opening. If it passed through at any angle without any pressure exerted, it was considered smaller than the opening.

Size of Test Samples

The large particles and the heterogeneity of solid waste made it desirable to use large test samples to increase the analytical accuracy and reproducibility. At the same time it was important not to get too large a sample to avoid possible overloading of any screen. If a screen became overloaded, the particles on it would be crowded and the respective particle tumbling action would be reduced. This would reduce the probability of the particles obtaining the proper alignment to fall through the screen aperture in a given time. In addition, overloading sometimes caused the particles to mat together [3,25].

In choosing the size of a test sample, consideration must be given to the characteristics of the material, its screenability, and the range of particle sizes present. For example, in making a sieve analysis of a material representing the product from a crusher (which contains a range of small particles), a sample of 1 to 2 lbs. may be required. For coarse aggregate, up to 150 lbs. or more might be necessary, while for finely ground material, a sample of 0.055 to 0.220 lbs. is usually sufficient. Obviously, the density of a material is very important. For example, a 6.1 cu. in. sample of powdered iron would weigh approximately 0.86 lbs. while the same volume of diatomaceous earth would weigh only 0.11 lbs. [3].

The volume of a test sample should be such that no sieve is overloaded to a point where there is crowding of oversize and near-mesh particles on the sieve surface. Overloading is most likely to occur in testing materials which have concentrations of particles close to one size or where the entire sample is within a narrow size range. In such a case, the size of the sample should be determined by the capacity (without overloading) of the sieve retaining the largest amount of the sample. At the same time, the sample must be large enough to permit retention of a measurable amount of material on each sieve, particularly on the control sieves. In making a sieve analysis of medium or fine material, it is best not to use too large a sample. A smaller sample, properly taken and carefully reduced, will usually give more accurate and consistent results, while a larger sample might overload one or more of the sieves. The reverse may be true when testing coarse materials, such as refuse or coarse aggregates, where larger samples are required to constitute a representative portion.

There are several ways to determine the proper size of test samples. The first is to observe the material during the screening process to make sure none of the sieves are overloaded to a point that the particles are not receiving adequate tumbling action. The ideal sample size for screens with large openings is one which would cover each sieve, approximately one particle deep at the end of the sieving process [26,33].

Cadle [25] and the ASTM Manual on Test Sieving Methods [3] recommended another method to determine the correct sample size. With a sample splitter, samples of various weights (e.g., 0.055, 0.110, 0.220, 0.330 and 0.440 lbs.) are obtained. Then each sample is sieved for a period of approximately 5 minutes, preferably on a mechanical sieve shaker. A comparison of these results provided a suitable sample size. For example, if the test with the 0.220-lb. sample provided approximately the same percentage passing the finer sieves as the 0.110-lb. sample, whereas the 0.330-lb. sample showed a lower percentage passing through the finest sieves, then this would be an indication that the 0.330-lb. sample was too large, and the 0.220-lb. sample would be satisfactory. Once the correct sample size is determined for a particular test, the same size should be used for all similar tests.

The above method assumes there is no experimental error in sampling and all of the subsamples have identical material with identical particle size distributions. This assumption is correct for homogeneous material with small particle sizes, such as most chemicals and soils. Unfortunately, the assumption is not correct for the large particle and heterogeneous solid waste, unless very large samples are used. In such a case, the size of the sample would be too large and subsequently impractical for the existing sieve equipment.

A table of suggested sample sizes for use when standard sample sizes have not yet been established is provided in the Manual on Test Sieving Methods [3]. It suggests these sample sizes be verified by the procedure outlined immediately above before adopting them as a standard. The table suggests a sample size by bulk volume for various sieve sizes of an 8-in. diameter sieve. The recommended weight of material can be calculated by multiplying the indicated volume by the bulk density, which is readily obtained for many particulate materials from another table of the manual. Table 7 provides salient information from this table, with appropriate interpolations and adjustments for the larger Gilson screens. Unfortunately, this table and the similar table in the ASTM manual are confusing, since various sieve sizes are provided and the manual does not mention whether the sieve size represents the maximum or the mean particle sizes of the material; nor does it mention the maximum sieve size which could be used. If it is assumed the latter is the appropriate definition, then the suggested bulk volume for the Gilson screen with a 4-in. maximum sieve is 1.6 cu. ft. The proper sample weight for raw solid waste with a density of 100 lbs. per cu. yd. would be 6.10 lbs. For loose shredded waste with a density of 400 lbs. per cu. yd., the sample weight would be 24.39 lbs.

The sample weight obtained from the above table for shredded waste (24.39 lbs.) is considerably greater than what previous investigators used with solid waste. A comparison of sample sizes shown in Table 8 also includes the recommended sample sizes and the calculated unit screen loadings for other refuse and materials, such as soil and fine aggregate. The unit screen loading is obtained by dividing the sample size by the sieve screening area. This provides an indication of

Table 7

ASTM Suggested Bulk Volumes and Weights of Test Samples [3]

Standard Sieve Designation (in.)	Recommended Volume of Material for Test Sample (cu. ft.)		Recommended Weight of Sample (lbs.) for the Following Bulk Densities (lbs./cu. yd.)		
	8-in. diameter screen	Gilson screen[a]	100	200	400
8	0.508[b]	3.291	12.19	24.38	48.76
4	0.254[b]	1.646	6.10	12.19	24.39
2	0.127[b]	0.826	3.06	6.12	12.24
1	0.064	0.411	1.52	3.04	6.09
0.75	0.049	0.320	1.19	2.37	4.74
0.50	0.028	0.183	0.68	1.36	2.71
0.375	0.021	0.137	0.51	1.01	2.03
0.187	0.013[b]	0.087	0.32	0.64	1.29
0.094	0.008[b]	0.053	0.20	0.39	0.79
0.047	0.005[b]	0.034	0.13	0.25	0.50
0.023	0.004[b]	0.025	0.09	0.19	0.37

[a] Figures in this column were calculated assuming the same unit loading per sq. in. on the Gilson screen as the 8-in. diameter screen, but with a screen area of 6.48 times greater in size.

[b] These figures were interpolated from ASTM Manual on Test Sieving Methods [3].

Table 8

Test Sample Sizes Utilized by Previous Investigators

Reference	Type of Material Screened	Size of Sieves (in.)	Sieve Screening Area (sq. in.)	Size of Samples (lbs.)	Screen Loading (lbs./sq. in.)	Number of Sieves in Nest
Anonymous [42]	Compost	8" dia.	50.3	6.6-22	0.131-0.438	3
Oberaker [47]	Shredded Waste	6-3/4x4-1/2	28	0.03	0.001	6
Fess [49,50]	Shredded Waste	14-1/2x22-3/4	324	3.45-4.22	0.010-0.013	8
Jones [51]	Shredded Waste	18x24	432	8-10	0.019-0.023	4
Anonymous [53]	Shredded Waste	36x36	1296	126-162	0.097-0.125	3
Gawalpanchi [21]	Shredded Waste	probably 8" dia.	50.3	0.13-0.22	0.002-0.004	13
Results from Table 7	Raw Shredded	-- --	324 324	6.10 24.39	0.019 0.076	-- --
Lambe [23]	Soil	8" dia.	50.3	1.10	0.022	6
ASTM C 136 [33]	Fine Aggregate	8" dia.	50.3	0.22-1.10	0.004-0.022	6
ASTM D 2862 [34]	Granular Activated Carbon	8" dia.	50.3	0.22	0.004	6

the sieve loading but does not take into account the various densities of different materials or the sieve size. It also does not take into account the separate loadings on each sieve. In general, a higher unit screen loading is expected for larger particle sizes and higher density materials, as well as for a greater number of sieves.

Most of the investigators used sample loadings for shredded waste of less than 0.023 lbs. per sq. in. In the only exception, it was not clear from the reference whether the sample size represented a single sample or a summation of several samples. The recommended screen loadings for other materials vary widely. The recommended size of samples for granular activated carbon is given by ASTM [34] as 0.22 lbs. (0.004 lbs. per sq. in.). Lambe [23] recommended 1.10-lb. samples (0.022 lbs. per sq. in.) be used for soil, but suggested larger samples be used if the soil had many particles greater than the No. 4 sieve. ASTM recommends sample screen loadings for fine aggregate [33] from 0.004 to 0.022 lbs. per sq. in., while for coarse aggregate it recommends sizes from 0.022 to over 0.772 lbs. per sq. in. The maximum screen loading for fine aggregate of any sieve at the completion of the sieving operation is recommended at 0.009 lbs. per sq. in.

After reviewing various methods for determining the size of test samples, the preferred method for solid waste appears to be the first one discussed in which the screening action is observed through the open spaces between the sieves. The sample size can be determined by selecting different sizes of samples (by volume) and observing the screening action on each screen. The screen tray, which received a heavy loading to prevent the proper tumbling of the particles, controls the size of the sample. In general, the sample size was limited so that the screens above 1/2 in. had, at the completion of screening, no more than the equivalent of about one layer of particles over the entire area of the screen.

The sample sizes were chosen on a volume basis. The approximate volumes and the actual weight of samples used are listed in Table 9.

Table 9

Sizes of Sieve Test Samples Used in Research

Type of Sample	Approximate Volume of Samples (cu. ft.)	Weight of Test Samples (lbs.)	
		Range	Mean
Raw	2.5	4.712-16.545	10.240
Primary	0.75	1.347-4.992	2.603
Secondary	0.50	2.167-8.821	3.175
Rasp	0.50	4.656-8.023	5.646

It would appear the test samples of raw refuse exceeded the recommended sample sizes. In reality, the maximum size of these samples was determined by the capacity of the oven.

This was because only about 30 percent of these samples actually remained on the sieve at the completion of screening due to the considerable hand-sizing done during and prior to sieving.

Screening Procedures

The analytical procedures recommended by ASTM Manual on Test Sieving Methods [3], ASTM Designation E 389 [28], and ASTM Designation C 136 [33] appeared to be promising for use in sizing solid waste. The preliminary investigation with Fess [49] did not present any insurmountable problems with shredded waste. Therefore, these procedures were followed with slight modifications making them applicable for raw and shredded waste.

The screening procedures were as follows. After sample preparation, the test samples were weighed and recorded to an accuracy of at least 0.1 percent.[1] Since the Gilson mechanical screen holds only six of the ten screens, it was necessary to screen each sample twice. The first screening was for the coarse fraction and the second screening was for the fines. The first nest of selected sieves was placed in sequence with the coarsest sieve (4 in.) at the top and progressing sequentially downward to the smallest sieve (1/2 in.). Since only five screens were used for the run, the sieve space between the 4-and 2-in. sieves was left blank so that access was readily obtainable to the 2-in. sieve (access was also obtainable to the top sieve since the top of the machine was open). The test sample was incrementally placed on top of the 4-in. screen, in order not to overload any subsequent screen (the time period required to place the complete sample on the screen usually was less than one-half minute). The sample was then sieved for the required period of time using a timer.

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[1] In reality the test sample was recorded to the nearest 0.1 gm., which was an accuracy greater than 0.01 percent.

The progress of the screening was observed from the top and through the clear spaces between the screens. Any material plugging a hole in the top and coarsest screens was removed by hand and placed near the center of that screen for rescreening. The material of the heavily loaded screens was stirred by hand or with a ruler to increase the particle tumbling action. For those sieves which were definitely overloaded, the material on them was divided and an additional screen-run made. In determining whether a screen was overloaded, two criteria were used: the material on each of the larger sieves was limited to only one layer of particles; and for the smaller sieves, the movement of the material was observed during the screening. If the agitation did not appear sufficient to cause new particles to be presented to new holes, the screen was considered to be overloaded.

Particle sizes of the larger particles were tested directly by hand with 8-and 16-in. sieves and then placed in the appropriate plastic bag containing other particles of the same size range. Any material falling out of the machine during the screening was replaced on the appropriate sieve to be screened again. All bags and containers were emptied prior to the screening and the materials adhering to other particles were separated.

Each particle, approximately the size of the 4- and 2-in. sieve openings, was tested by hand to see if it could pass through the opening. The particles were presented at various angles and no pressure was applied. This was done prior to operating the mechanical screen on the raw waste, because such items as bottles and cans made considerable noise and possibly could break because of violent agitation. This was also done during screening for other materials of this size.

After the completion of the coarse screening, all of the material on or partially through each sieve was carefully removed and placed into tagged plastic bags. Material which fell on the floor was placed into the proper bag and, if necessary, rescreened. The bags were sealed and weighed shortly thereafter.

This procedure was repeated during the second run with fine screens using material in the pan from the first run. The coarse screens were replaced with the fine screens, with the 3/8-in. screen on top and the No. 30 screen at the bottom. The blank space was between the 3/8 in. and the No. 4 screens. Then the above screening procedure was repeated. At the end of this second run, the material on each screen and the pan was placed into separately marked plastic bags. The material imbedded into the finer screens was removed with a soft brass wire brush.

After the screening was completed, the dust and particles swept up and accounted for, the material in each bag was weighed to the nearest 0.1 gram. The net weight of each sieve fraction was calculated by subtracting the tare weight of the plastic bag. The sum of the sieve fractions was compared to the original weight of the sample. Since the weight of each fraction was determined to within 0.1 percent of the total sample weight, the maximum error of the test should not exceed 0.1 percent times the number of weighings, or approximately 1.2 percent of the total weight of each sample. If greater variation was found, the figures were rechecked for possible errors in weighing, calculating, plugging of sieve apertures, or accidental spilling losses. A copy of the *Sieve and Classification Test Data Forms* is found in Appendix E. The data for sample number 29 (P-11) are recorded on this form, as an example of the recording technique.

Duration of Sieving

Sieving is said to be a "statistical" operation because there is no end-point. Different sieving times will, as a rule, give different results. As the sieving time is increased, the sieve analysis becomes more accurate. The sieving time will not alter, however, the reproducibility to a large extent if the analytical procedures are routinely followed.

The required sieving time is closely related to the shape and number of particles on the screen. Large test samples cause the particles to become crowded, thus requiring greater sieving time. Sieving tests have shown a reduction in sample size is far more effective in reaching the true value than an extension of the sieving time. For example, in one test, Shergold found after nine minutes of sieving, the amount of material retained on a No. 14 sieve for a 4.409-lb. sample of sand was 13 percent more than the total weight of the true value. This discrepancy was reduced to 11 percent with 72 minutes of sieving. On the other hand, the reduction of the sample size to 0.551 lbs. brought the figure down to only 6 percent greater than the true value after nine minutes of sieving. The overloading effect was especially pronounced for smaller sieve apertures [2,23,24].

A thorough study of the physical laws that govern the sieving of fine particles was done by Whitby [2,26,30,98]. He showed that the mechanism of sieving under non-steady state conditions could be divided into two distinctly different regions with an intermediate transitional region, as illustrated in Figure 20. In region 1, there are many particles much smaller than the mesh openings on the sieve. As the particles much smaller than the mesh size are removed, the sieving mechanism goes through a transitional period and enters the second region. In this region, all of the particles less than the mesh size are eliminated from the residue and the remaining particles which can pass through

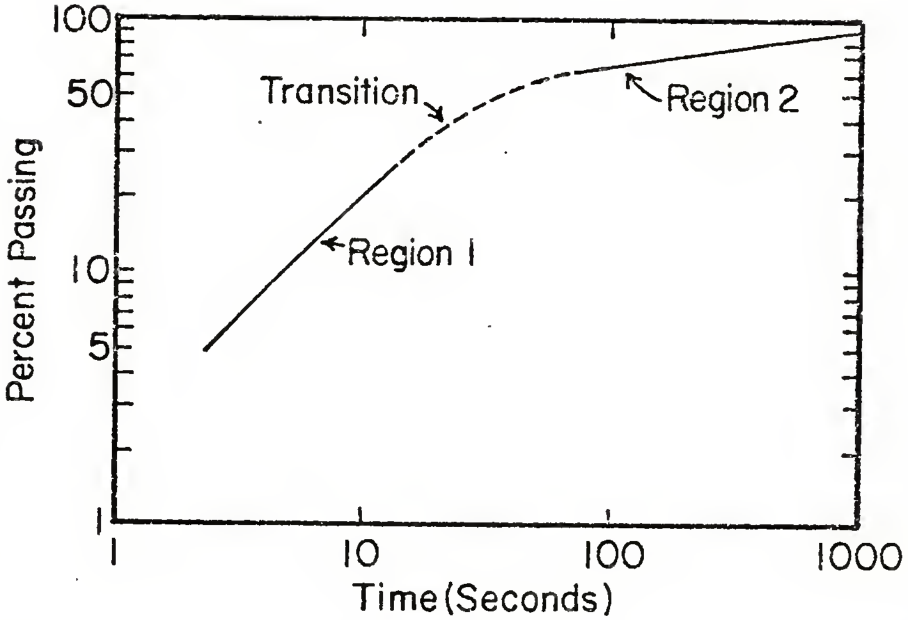

Figure 20. Cumulative sieving vs. period of sieving [2,26,30,86].

the sieve are very close to the mesh size. Region 1 of a typical sieving curve was found by Whitby to end about 10 seconds after sieving had begun while region 2 began about one minute after sieving had started.

The importance of the conditions selected for sieving analysis have been pinpointed in an extensive study by Whitby. It should be reemphasized that sieving is a highly empirical test because the sieving curve is not completely flat even in the second region of the process. However, more reproducible results can be expected in the second region because of the less extreme change in the percent passing the sieve in a unit time. Therefore, the time of sieving should be selected so that the measurements fall in this second region. Whitby suggested a good procedure would be to select, as an end point, the beginning of region 2. In the case of the curve (Figure 20), this would be between one and two minutes.

There is little information available on the desired sieving time for raw or shredded solid waste. Fess [49] screened his shredded waste samples for five minutes with the Gilson mechanical screen. He observed most of the separation was accomplished after one or two minutes. Gawalpanchi _et al_. [21] stated approximately 100 to 125 shakes were sufficient to segregate the material into fractions. This was apparently by hand-sieving. If this was the case, the amount of shaking they provided was only about two minutes.

Different sieving times are proposed for different materials. The ASTM _Manual on Test Sieving Methods_ [3] concludes that 3 to 5 minutes is usually sufficient for routine plant control tests. The recommended time for activated carbon [34] was 10 minutes, while for metal-bearing ores passing the No. 4 sieve [27], it was 3 to 30 minutes. Lambe [23] stated at least 10 minutes of hand-sieving is required for soils with small particles.

The ASTM procedures also note a specific time of screening cannot be used for all materials. It recommends the end point for different materials be established by experimentation. ASTM cautions that prolonged sieving times should be avoided when testing friable materials subject to degradation [3,28].

The ASTM manual suggests two methods for determining sieving time. The first method requires obtaining separate subsamples from the gross sample and sieving each subsample for different time periods between 5 to 20 minutes. The length of the desired sieving time is then obtained from tabulated results. Unfortunately, this method cannot be used for solid waste, since each subsample is different because of the large particles and heterogeneity of the material. In addition, a significant fraction of solid waste is highly friable and may make the results meaningless.

The second method of determining the screening time is to define the endpoint when an additional period of sieving fails to change the weight on any of the sieves by more than a predetermined percentage. The ASTM Manual on Test Sieving Methods [3] recommends one minute and 1.0 percent for most materials, but notes that when the ultimate in accuracy is desired, the time should be 5 minutes and 0.5 percent. The one minute and 1.0 percent combination is also specified by ASTM Designation C 136 [33] for aggregate. ASTM Designations E 276 and E 389 for metal-bearing ores [27,28] are even more restrictive, requiring 0.3 percent for "additional periods of shaking." They note this requirement may be meaningless for highly friable materials and the end-point should be determined experimentally.

The latter procedure for determining the sieving time appears to be more applicable for solid waste than the former, but the friability of the material may present some problems.

Long sieving times should be avoided for solid waste in order not to disintegrate many of the particles. At the same time, the above required percentages appear highly subjective and somewhat meaningless. During the initial screening of shredded waste, it was observed very little material was passing through the sieves after two minutes of time and almost none after four or five minutes. Thus, the five minutes appeared to be a logical sieving time. It was the same time as Fess used and considerably greater than the time used by Gawalpanchi _et_ _al_. [21]. In addition, it was well within Whitby's region 2 and at the conservative end of the 3 to 5 minute range as recommended by the ASTM _Manual on Test Sieving Methods_ [3]. Each sample screened in this research was sieved for a 5-minute period.

Refuse Composition Classification Techniques

In order to determine the particle size distributions of each category of solid waste, it was necessary to screen and classify the waste into its various components (e.g., paper, plastics). Two different procedures were available. The first procedure initially sized the waste into various fractions and then classified each fraction into its respective components. The second procedure first required the classification of the test sample into the various categories and then the screening of each category separately, to obtain their size distributions. The latter method was considerably more time-consuming than the first, since it required separate screenings for each category. Thus the former method was chosen for convenience. This classification procedure was selected for both the raw and the shredded refuse samples and for all fractions of the waste including the fines. The results were recorded on the same form as used for the sieve analysis, a copy of which is in Appendix E.

No information is available on the accuracy and reproducibility of any classification scheme. Thus, one should be selected which theoretically appears to be reasonably accurate and reproducible. The scheme provided on page 74 was used in this research, with several exceptions. Three categories were further subdivided and an additional one added for a total of thirteen separate categories. The scheme used follows.

1. food;
2. garden waste;
3. cardboard;
4. other paper;
5. plastic, leather and rubber;
6. textiles;
7. wood and limbs;
8. ferrous metal;
9. non-ferrous metal;
10. glass and ceramic;
11. rock and gravel;
12. ash, earth, and sand; and
13. miscellaneous.

It was felt that paper, normally the largest category, should be further subdivided into two additional categories of similar nature, e.g., cardboard and other paper. Cardboard was defined as a single sheet of paper greater than 0.035 in. in thickness. The metal category was also divided into ferrous and non-ferrous. The ash, dirt, brick and stone category was subdivided into: (1) rock and gravel, and (2) ash, earth, and sand (based on a definition that ash, earth, and sand were less than the No. 8 sieve, and rock and gravel were greater than the No. 8 sieve). The last category added was miscellaneous which provided for occasional uncategorized items. Detailed definitions of each category (with examples) are found in Appendix F.

This classification scheme was straightforward and most of the components could be easily recognized. One problem area was bi-component particles. When bi-components were encountered, a decision was made whether the secondary material had appreciable weight. If it did, the items were weighed separately or the weights estimated. If it did not, the object was considered as the primary material. In reality, few bi-components were encountered for shredded waste since shredding tends to separate the components. However, ignoring the bi-components for raw refuse would introduce a significant error and thus attempts were made to classify all of the larger bi-component particles.

A few materials were somewhat difficult to identify. Thick, clear plastic was differentiated from glass by hardness (scratching). Glass was further differentiated from sand by the color, opaqueness, and the sharpness of corners. Shredded cardboard and wood sometimes appeared as paper and shredded twigs, respectively. These particles were closely observed in order to determine whether they appeared to originate from larger and thicker particles.

The finer fractions presented another problem. Many investigators indicated a considerable amount of time was required to classify the fines, since there were so many particles to physically identify. A different classification scheme was required to estimate the composition of these fractions. Initially, an estimate was made of the component of each fraction by spreading the material in a large pan and visually estimating the composition. The inaccuracies of this method were readily apparent; this procedure was soon changed and the previous samples reanalyzed. The improved method consisted of taking subsamples of the No. 30 or greater sieve fractions and classifying the complete subsample, utilizing tweezers where necessary. The subsamples were then used to estimate the composition of sieve fraction. A separate experiment was provided to determine the size of the subsamples, and the results are presented in Chapter V.

The classification of the pan fraction (less than No. 30 sieve) presented another problem. Most of the particles in this sieve fraction were too small to classify on a particle-to-particle basis. Instead, it was decided to visually estimate the composition, after some preseparation. Most of the light fractions (paper, garden) were removed from the heavy fractions (sand, glass) by using a fine household screen and shaking with a tumbling action (the fines matted together).

Thus, the two subfractions which were produced were weighed and the components visually estimated.

The classification techniques were formulated as follows:

(1) Each sieve fraction (e.g., 1 to 2 in.) was dried again for several hours and then weighed to the nearest 0.1 gm.

(2) Each dried fraction was spread on a metal pan for separation and identification.

(3) The components were classified according to the classification scheme described in Appendix F, utilizing the techniques discussed in this section.

(4) Each category was weighed to the nearest 0.1 gm.

(5) Appropriate size subsamples were randomly collected from the smaller particle size sieve fractions and each subsample was classified and weighed. Estimates were made for the composition of that fraction.

(6) The weights of each of the components of the larger sieve fractions were summed and compared to the sieve fraction's original weight. If the difference was greater than 1.0 gm., the components were reweighed in an attempt to identify the error.

CHAPTER IV

DENSITY AND COMPRESSIBILITY ANALYSES

Introduction

It would be helpful to discuss the particle structure of solid waste before discussing its density and compressibility. The principles provided in soils engineering appear usable for solid waste. Thus, a good portion of this material was directly obtained from Spangler's Soil Engineering [99] and Tuma and Abdel-Hady's Engineering Soil Mechanics [100]. Most of the definitions are similar to those of soils. The only exception is that soils usually contain significant amounts of free moisture in their pores. This is not true for refuse; the moisture contained in refuse is usually absorbed in the refuse particles. Almost the only time moisture is contained in refuse pores is when an artificial barrier prevents the moisture from draining. In addition, the particles in soil are usually inorganic and rigid, while those in refuse are mostly organic and flexible.

It was pointed out earlier that refuse is a highly heterogeneous mass consisting of different materials of various particle sizes and shapes, and with different physical and chemical properties. Refuse can be visualized as an assemblage of particles interspaced with open air-spaces called voids or pores. The solid portion of the mass is referred to as the particle skeleton. The pattern or arrangement of the individual particles is called the particle structure.

The void spaces in the refuse are interspersed throughout the framework of the solid particles. An idea of the porous nature of refuse and the relationship between the solid matter and void space can be visualized by imagining a cubical container of refuse, 1 ft. on each side, filled with balls 2 in. in diameter spaced normally to each other. The balls represent the solid particles in a cubic foot of refuse and the spaces between them represent the air voids.

The volume, V_m, of a given sample of refuse can be conveniently expressed as

$$V_m = V_s + V_v = V_s + V_w + V_g \tag{1}$$

where V_s = volume of solids,
V_v = volume of voids,
V_w = volume of water, and
V_g = volume of gases (air).

The weight, W_m, of the same refuse sample is

$$W_m = W_s + W_w + W_g \approx W_s + W_w \tag{2}$$

where W_s = weight of solids,
W_w = weight of water, and
W_g = 0 = weight of gases (air).

Two volume ratios are of practical significance - the void ratio and porosity. The void ratio, e, is the ratio of the volume of voids to the volume of solids,

$$e = \frac{V_v}{V_s}\text{ , and is dimensionless.} \tag{3}$$

The porosity or percent air voids, η , is the ratio of the volume of voids to the total volume of refuse,

$$\eta = \frac{V_v}{V_m}\text{ , and usually expressed as percent.} \tag{4}$$

In contrast, the percent of total volume of refuse which is occupied by solid particles is called the percent solids. The percent solids plus the porosity equal 100 percent.

In engineering practice, the weight per unit volume is frequently called the density of the material. The term is used synonymously with the terms unit weight and specific weight. The term density, as defined here, also is widely used with respect to solid waste. However, in certain scientific fields, specifically chemistry and physics, density is defined as mass per unit volume which is equal to weight per unit volume divided by the gravitational constant. In this research, the term density will be defined as weight per unit volume as is commonly used in engineering.

The density of solid waste can exhibit different values depending on the moisture content. It is sometimes expressed as wet weight density, γ_m, which is the total weight of the material (including water) divided by the total volume,

$$\gamma_m = \frac{W_m}{V_m} = \frac{W_s + W_w}{V_m} . \qquad (5)$$

When the wet weight density is given, the moisture content also should be provided.

The more commonly expressed density is the dry weight density, γ_d, which is the weight of only the solid particles divided by the total volume,

$$\gamma_d = \frac{W_s}{V_m} . \qquad (6)$$

It is also called the apparent or bulk density.

In addition, density can be expressed as the unit weight of the solid particles, γ_s,

$$\gamma_s = \frac{W_s}{V_s} . \qquad (7)$$

In this case, it is called the true or absolute density.

Because solid waste is not rigid, it can produce numerous bulk densities depending on the pressures applied to the material to reduce the void space. The bulk density also widely varies because of the different compositions of the waste irrespective of its porosity.

The bulk densities which can be expected for densely packed solids are close to those obtained for solid blocks of the same material (true density). The approximate densities of some common solids are listed in Table 10. This table is for relatively dry, densely packed solids which closely approach the true density for most of the listed items.

The table indicates the average density of very dense bales of paper is approximately 1,500 lbs. per cu. yd. Steel

Table 10

Approximate Densities of Common Solids [70,101]

Solids		Density Range (lbs. per cu. yd.)
Paper		1,160-1,915
Metal:	Aluminum Alloy	4,460-4,920
	Iron Alloy	11,620-14,330
	Copper Alloy	13,500-14,850
Glass		4,050-4,910
Porcelain		4,320-5,120
Plastic		1,780-3,240
Wood		324-1,916
Leather		1,295-1,750
Rubber		1,620-2,970
Cereal		700-1,300
Fat		1,540-1,650
Wool		1,350-2,215
Masonry		2,700-4,375
Brick		2,380-3,370
Concrete		3,024-4,131
Ash, Cinder		1,080-1,215
Soil		1,701-3,402
Baled Straw and Hay		540

scrap, in comparison, has a density of approximately 13,000 lbs. per cu. yd. It should be remembered such densities can be expected only if almost all of the voids in the bales are eliminated. In the absence of voids, mixtures of refuse containing a variety of different materials in different proportions should have densities which are between the minimum and the maximum value of the densities of the material.

The bulk density of a material can never be increased sufficiently to equal the true density of a solid mass having the same specific gravity as its particles. There will always be some voids in the mass due to the irregularly shaped particles. The only way such a limiting density could be obtained is if the particles were true cubes or parallelepipeds (similar to a child's building blocks), stacked together without air voids. Obviously, this condition cannot occur.

The true density of refuse can be estimated using the average densities of the different components as found in Table 10. This was done and the salient information is shown in Table 11. Average dry weight refuse compositions from two sources, National Center of Resource Recovery [67] and U.S. Environmental Protection Agency [7], were utilized.

Table 11 provides several interesting points. First, the column headed by "Contributing Density" represents the weight of a cubic yard of compacted refuse (relatively free of air voids) which is contributed by each refuse component. This is the product of the calculated true density and the

Table 11

Calculated True Density of Refuse

Category	Average Density (lbs. per cu. yd.)	Estimated Refuse Composition (dry weight percent) References NCRR [67]	EPA [71]	Contributing Density Range (lbs. per cu. yd.)
Paper	1,538	35.0	38.4	443-606
Glass	4,480	9.0	13.2	114-209
Ferrous	13,095	7.0	11.6	89-183
Aluminum	4,690	0.7	0.9	9-14
Other Non-ferrous	14,175	0.3	0.5	4-8
Textile	1,783	2.0	1.8	25-28
Rubber	2,295	1.0	3.6	13-57
Plastic	2,610	1.5	4.6	19-73
Others:	847	43.5	25.4	401-551
Wood	1,120	--	(4.5)	71
Food	1,000	--	(9.6)	152
Yard waste	540	--	(10.5)	166
Miscellaneous	1,500	--	(0.8)	13
TOTAL		100.0	100.0	1266-1578
Calculated True Density (lbs. per cu. yd.)		1266	1578	

composition of each component. Accordingly, the contribution by each component is in proportion to its composition.

The true density of refuse was calculated at 1,266 to 1,578 lbs. per cu. yd., with an average of 1,422 lbs. per cu. yd. Theoretically, these figures are the highest densities which can be produced for dry refuse with the highest pressure balers. In order to obtain them, the balers must have sufficient pressure to crush the refuse particles, thus eliminating almost all of the air voids. A value of 2,031 lbs. per cu. yd. is obtained when the average results are adjusted for moisture (30 percent on a wet weight basis). This is comparable to the 2,160 lbs. per cu. yd. which APWA [70] calculated as the highest density obtainable by high pressure balers.

Several other terms are related to density and should be defined. The specific gravity, G_m, of a refuse sample is the ratio of its weight to the weight of an equal volume of distilled water at 4°C.

$$G_m = \frac{W_m}{V_m \gamma_o} = \frac{\gamma_m}{\gamma_o} \qquad (8)$$

where γ_o = density of distilled water at 4°C.

Similarly,

$$G_s = \frac{W_s}{V_s \gamma_o} = \frac{\gamma_s}{\gamma_o}\,, \qquad (9)$$

where G_s = specific gravity of the solids, which also is called the true or absolute specific gravity.

Since refuse is highly porous, it has an apparent or bulk specific gravity, G_a, similar to density. This is defined as the ratio of the dry weight of a unit volume of refuse to the unit weight of water,

$$G_a = \frac{W_s}{V_m \gamma_o} = \frac{\gamma_d}{\gamma_o} . \qquad (10)$$

The specific volume, commonly used in Europe, is the inverse of density and is usually expressed as cubic yards per ton.

It can be shown that the density is practically the same whether the refuse is composed of large particles or small particles, provided other characteristics, such as composition, particle shape and arrangement, remain constant. For example, the 2-in. diameter balls in an imaginary refuse would number 216 and occupy a total volume of 0.524 cu. ft. if the balls were spaced normally to each other. A similar volume would be obtained for 1-in diameter balls for the same arrangement, but 1,728 balls would be required in this case.[1]

Although the density of a material is not affected by difference in the size of particles (assuming similar particle shapes), it is influenced appreciably by the particle arrangement. Suppose, for example, the balls composing the imaginary refuse are rearranged by moving each tier a half diameter to the right (or left). In the new arrangement, the volume of the balls (solid particles) is still 0.524 cu. ft., but the total volume of material (solids plus voids) is now reduced to 0.911 cu. ft. Hence, the void ratio is reduced from 0.910 to 0.738. Since the specific gravity of the particles is not altered in the process of rearrangement, the density of the imaginary refuse is increased. The density could be further increased by sliding each tier of balls a half diameter in the direction normal to the previous move.

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[1] This indication is also borne out by the recognized fact that a basket of small potatoes weighs about the same as a basket of large ones. In addition, the density of coarse gravel with fairly uniform sized particles is about the same as the density of a fine sand or silt of the same material, i.e., specific gravity and particle shape.

The density of refuse is also increased when it consists of particles of various sizes, rather than particles of uniform size. This principle is illustrated by the fact that, in the case of the imaginary refuse, smaller balls can be placed in the void spaces between the larger balls. The introduction of the small balls increases the volume of the solid material, but it does not change the total volume (solid particles plus voids). Therefore, the void ratio is decreased and the density is increased by this process. The greatest possible density is obtained by continuing to put smaller balls in the remaining spaces until particles of microscopic size have been included.

The overall wet weight density of a waste mixture can vary significantly. In the absence of any swelling, the moisture absorbed by the solids adds to their weight but does not produce an increase in their volume.

The weight of the moisture contained in refuse may be high. For example, it is conceivable that the contribution of moisture to the density could be greater than 50 percent. Such a contribution would be especially noticeable if the refuse contained a high proportion of highly absorbent materials, such as paper and textiles. Materials such as metal have little or no tendency to absorb moisture; therefore, the increase in density due to moisture is unappreciable when the refuse contains a high metal content.

It is inconceivable refuse would swell to any extent due to increased moisture content, since swelling usually does not occur in large particle materials (as found in refuse). Also, most of the components of refuse do not swell with moisture. It is doubtful the few remaining components would swell to any significant amount.

Several frequently encountered terms related to the process of soil volume change are defined below and will be used in this study for refuse:

(1) The compression or compressibility (volume change flexibility) is the volume decrease due to a unit load [100]. Compression usually results from static loads.

(2) The consolidation (volume change velocity) is the rate of decrease in volume with respect to time [100]. Consolidation usually implies long-term static loads, which often vary from days to years.

(3) The compaction or compactibility is a volume decrease method utilizing impact loads [99]. It is used to determine the optimum moisture content and the maximum density for soils.

Methods of Previous Investigators

Density

In reviewing the literature, several references were found concerning the determination of density of various refuse types. Unfortunately, although all used similar procedures, the details for each varied greatly. The basic procedures were to determine the volume and the weight of a specific quantity of refuse and then express those values as weight per unit volume, usually as pounds per cubic yard.

No standard test has been adopted to measure the density of refuse. ASTM has adopted a number of standards for other materials and several appear to be readily usable for solid waste. ASTM Designation C 519, "Test for Density of Fibrous Loose Fill Building Insulation" [102], requires a wooden container to be used with varying sides, but in no instance less than 18 in. x 14 in. x 4 in. The container is closed on the bottom of the large area side and open at the other end to permit filling. The insulation is poured into the container and leveled by hand. Care must be taken not to compress the insulation or leave large air voids on the surface of the material. The depth of the insulation is then determined by utilizing a depth gage. Five measurements are required for each test, one near each corner and one in the center to establish the average. A scale with an accuracy of at least 0.5 percent of the sample weight is used. The test is repeated three times utilizing fresh material and calculating the density each time.

ASTM Designation C 520, "Density of Granular Loose Fill Insulations" [103], uses a light-weight rigid box having a volume of exactly 1 cu. ft. All inside dimensions are 12.00 ± 0.04 in. The insulation is placed in the box, until it overflows, by means of a shovel or scoop and the insulation is discharged from a height not exceeding 2 in. above the top of the measure. Caution must be taken to prevent segregation of the various particle sizes of the sample. The surface of the insulation is leveled off so the slight projections of the larger pieces of coarse insulation approximately balance the larger voids on the surface below the top of the measure. Caution must also be taken not to compress the sample. A scale with an accuracy of at least one percent of the sample weight is used. This procedure is repeated three times with fresh material and each density calculated.

Densities have been determined in the field for in-place soil samples by digging a small hole (4 in. diameter) and then carefully removing all of the material. After weighing this material, a representative sample is removed for moisture determination. The volume of the hole (which is the volume of the soil sample in the undisturbed state before removal) is measured by filling the hole with some substance (sand, heavy oil, or water in a balloon) whose specific gravity is known. The weight of the substance required to fill the hole is then converted to volume. Then the wet and dry soil densities are calculated [99].

In the laboratory, the densities of undisturbed soil samples are obtained by weighing the soil sample and determining its respective volume by liquid displacement. Both kerosene and water are commonly used liquids. In order to prevent the soil from absorbing the liquids, it is usually necessary to coat the sample specimen with paraffin and a correction made for the amount of paraffin used [99].

Also, the density of soil can be obtained by the use of the Proctor compaction test. This test is utilized to determine the optimum moisture content for compacting soils to maximum densities. The sample is compacted in a metal cylinder of known volume (usually 1/30 cu. ft.). The weight of the material is measured and the resulting density calculated [23,99].

Di Filippo and Malina [104] used a cylinder to determine the density of finely ground refuse (passing a 0.236-in. rasp in a Wiley mill). The dimensions of the cylinder were not given. In order to remove any compactive effort, the size-reduced material was placed in the cylinder, which was slanted to the horizontal position. The cylinder was then placed upright and the volume and weight of the sample determined. All materials, except food waste, were dried prior to the test.

Higginson [7,18] and Stirrup [56] described a technique for determining the density of various types of waste (larger items excluded), using a bottomless wooden cube containing exactly 1 cu. yd. The cube was carefully filled to the top with undried refuse using a shovel, taking care not to compress the material. A board was drawn lightly across the top to skim off or remove any material protruding above the edge of the container but, under no circumstances, was any refuse pressed down into the container. The density was then calculated from the weight of the material used. Ham and Reinhardt [105] observed several similar cubes during their 1972 visit to Europe.

Researchers at Sulfur Spring, Texas [53], determined the density of raw refuse using 55-gallon drums. Refuse was placed loosely in these drums, the respective volumes and weights measured, and density values computed.

The densities of various refuse constituents were determined at the Gainesville compost plant during a waste classification study [10]. A 328-lb. sample of raw refuse was separated into its constituent parts and each item was placed into refuse containers marked for the proper category. The weight and volume of each category was measured at the completion of the separation and the density then calculated.

Researchers at the Gainesville compost plant also determined the density of compost from storage piles [11]. These samples were collected in the form of chunks. The chunks were placed in plastic bags, the air removed with a vacuum pump, and then the bags immersed into water. The volume measurements were made using the water displacement method.

The density of shredded refuse was determined at the Gainesville compost plant by placing a known weight of material (338.5 tons) in digesters for three days and then measuring the volume of the material (1,185 cu. yds.). The material was placed in the digesters by the tripper-conveyor. The volume was estimated by using the width of the digester (20 ft.), approximating the length of the sample (223.5 ft.) and the average depth (7.16 ft.) as determined by multiple measurements. Moisture contents were determined from grab samples [11].

Densities at landfills are usually determined by weighing the refuse upon arrival and by calculating the volume of compressed material using topographical surveys before and after compression. This was done at Madison, Wisconsin [19], and Crawford County, Ohio [51], for raw and shredded waste. Aerial surveys were used at San Diego [106]. Ham and Reinhardt [105] reported a variation for density determination in Great Britain where previously compressed refuse was dug from a landfill and weighed. The in-place volume was estimated by back-filling the hole with a known volume of sand.

In determining landfill densities, correction should be made for the amount of earthen cover used if the actual compressed density of the refuse is desired. Unfortunately, only a few of the references reviewed mentioned whether this correction was made.

Refuse densities are usually determined from refuse collection vehicles by dividing the measured weights of the refuse by the designated capacity of the truck. Sometimes the volume of the truck is actually measured. The former method may present considerable error for packer trucks because it is difficult to determine if they are full.

The density of baled refuse is calculated by weighing each bale and then determining the respective volumes using a ruler. Cummings and Reid [72] used this method to determine the density of compressed refuse from apartment house compactors. The procedure also was followed by APWA [107] and the City of San Diego [106] in determining the density of bales of refuse compressed by balers. APWA determined the density of bales in the compression chamber by measuring the length and width of the chamber and determining the exact position of the third ram.

Many articles were found which gave the densities of various types of refuse. A compilation of these data is found in Table 12. Some caution must be exercised in using this table. Most of the articles reported average densities. The range column, therefore, may not actually represent the true range of the densities. Also, the values in the average column are the arithmetic mean of all the values reported for that process. In addition, it was necessary to estimate the dimensions of several pressure plates in order to calculate unit pressures.

The data definitely show higher densities are achieved with greater amounts of applied pressures. They also show higher densities are obtained for smaller particle sized refuse. In almost all cases, the density of shredded waste was found to be greater than the density of raw refuse of

Table 12

Reported Densities of Various Types of Refuse

Process	Type of Refuse	Range of Maximum Applied Pressures (psi)	Density (lbs. per cu. yd.)		Selected References
			Range	Average	
Containers (Loose State)	Raw	0	50-450	220	10,37,53,69,106, 116,119,125,127
	Shredded	0	260-1,050	600	11,37,38,40,56,69, 114,115,125,127
Open Bed Trucks (Loose State)	Raw	0	370-380	375	109,125
	Shredded	0	400-500	450	127
Compactor Trucks (Under Pressure)	Raw	8	300-750	440	69,109,110,115,119
Compactor Trucks (Ejected Refuse)	Raw	0	200-1,000	430	56,69,114,115
Landfilled (Bulldozer)	Raw	7-13	470-1,231	840	19,56,74,106,108, 111-113,116,117, 119,125,127
	Shredded	7-13	700-1,667	1,040	19,108,115-117,127
Landfilled (Compactor)	Raw	26-241	1,200-1,383	1,260	108,111,112
Home Compactor	Raw	8	600	600	126

Table 12 - Continued

Process	Type of Refuse	Range of Maximum Applied Pressures (psi)	Density (lbs. per cu. yd.)		Selected References
			Range	Average	
Baler (Low Pressure)	Raw	20-80	370-1,200	710	37,69,72,106,125
	Shredded	140	1,450-1,650	1,570	106,118
Baler (High Pressure)	Raw	650-6,000	925-2,916	1,740	69,70,107,108,119-125
Compost	Compost	0	420-1,700	1,060	11,61
Conventional Incinerator Ash	Ashes	0	521-1,627	870	108
High Temperature Incinerator Ash	Ashes	0	2,750	2,750	108

similar processes. This appears go be in conflict with an earlier statement that the density of refuse should be the same whether the refuse is composed of large or small particles. However, it was stated this was true only if the other characteristics, such as composition, particle shape, and particle arrangement, remained the same. Obviously, the particles from shredders will have different shapes than particles from the raw product. For example, we do not obtain small bottles and containers when large bottles and containers are shredded.

Solid waste contains a high proportion of materials with large voids. Therefore, a decrease in void space and thus in volume can be achieved by breaking up waste items, such as large containers. In no case can size reduction provide a means of eliminating all voids from waste or other material.

It should be recognized that shredders are not principally designed as a method for volume reduction, and a reduction in the volume of compact solids such as stacked paper or logs cannot be achieved by shredding. In fact, when such items are shredded they occupy an appreciably larger space than before shredding due to the introduction of voids not initially present in compact materials.

Another interesting fact, shown in Table 12, is the density of aged compost is greater than the density of fresh compost. This was expected since biological processes (composting) reduce the particle size.

Several researchers have screened various types of refuse and measured the density of the sized fractions. Higginson [18] found the density of the sized fractions of raw refuse under 1/2 in. was 850 lbs. per cu. yd., while the density of the 1/2 to 1-3/4 in. fraction was 675 lbs. per cu. yd. Most of the material at both of these size ranges was cinders and ashes. Rena [37] also determined the density of size shredded waste, as shown in Table 13; however, no information was given on the grate opening.

Table 13

Density of Sized Shredded Refuse [37]

Screen Size (in.)	Percentage by Volume	Percentage by Weight	Density (lbs. per cu. yd.)
Below 1/2	11	24	633
1/2 to 1-1/2	46	42	264
1-1/2 to 3	38	30	251
Above 3	5	4	229
Total	100	100	286

The density was determined for various components of refuse under uncompacted conditions, as noted in Table 14 (these densities were determined under wet weight conditions). The table gives an indication of the effect each component has on the total uncompacted refuse. As expected, the fine materials (rock, gravel, and food waste) had the highest wet

Table 14

Wet Weight Densities of Various Components of Refuse

Refuse Component	Density (lbs. per cu. yd.) Range	Average	References
I. Combustibles	---	134	10
A. Food waste	636-1,540	980	10,18,109
B. Garden waste	---	178	10
C. Paper waste	119-135	127	10,18
1. Salvageable	---	121	10
a. Paper	117-135	126	10,18
b. Cardboard	---	92	10
c. Magazine	---	326	10
2. Non-salvageable	---	118	10
D. Plastic, rubber and leather	63-81	72	10,18
E. Textile	216-233	225	10,18
II. Non-Combustibles	---	362	10
A. Metal	222-270	246	10,18
1. Ferrous	130-229	180	10,37
2. Non-ferrous	171-240	206	10,83
B. Glass and ceramic	526-730	628	10,18
C. Rock and gravel	---	1,845	83
D. Ash, earth, sand and brick	675-1,400	984	10,18
E. Miscellaneous	---	595	18
III. Bulky	200-308	254	18,63

density while those items with considerable voids (plastic containers, tin cans, and paper waste) had the smallest wet weight density. The density of the material varied considerably with the arrangement of the particles. For example, Higginson [18] found that loose paper had a density of 135 lbs. per cu. yd.; but if the paper was folded and flattened, the density was increased to 1,500 lbs. per cu. yd. In the latter case, more voids were eliminated.

Compressibility

Every material undergoes a certain amount of deformation (strain) when a stress is applied. If the material was truly elastic, it would obey Hooke's Law, which is:

$$\sigma = E\varepsilon \ , \tag{11}$$

where σ = applied stress (psi),
E = Modulus of Elasticity (psi), and
ε = strain (in./in.).

If it was truly elastic, the material would regain its initial dimensions when the stress was removed. Many materials are not elastic and do not recover all or even a major proportion of the strain when the stress is removed. Refuse is one of those materials [99,100].

The usual procedure for representing the above relationship is to determine the modulus of elasticity (E) for an elastic material or graphically show the stress-strain curve for inelastic materials. Different forms of the latter relationship are usually provided for special materials, e.g., the void ratio versus pressure is often used in soils. With respect to solid waste, this relationship is usually expressed as applied pressure versus bulk density. It is sometimes expressed as applied energy versus volume reduction (or bulk density).

Unlike steel and concrete, in which strain develops almost instantaneously with the application of stress, the strain in soil and refuse develops over a period of time after the pressure is applied. The primary reason for this time lag in soils is that water confined in their voids has to be squeezed out before the volume of the voids can decrease. This can take several years to be completed for fine-grained clays. In relatively coarse-grained soils, the pore water can escape rapidly and the time lag between application of pressure and the development of strain is relatively small. Since refuse has large particles and relatively no free moisture, the time lag should be small.

When pressure is applied to solid waste, its volume is reduced and its density increased. This is accomplished by the crushing, deforming and relocating of the individual particles, reducing the void spaces at the interface between different solid particles and those present inside hollow waste objects, such as containers. The distortion of the particles is largely elastic and consequently reversible, while the rearrangement and fracturing of the particles contribute to volume changes which are irreversible.

The compressibility of refuse is dependent on the porosity and the specific densities of the individual waste components. For example, if a given load was made up of solids which occupied 50 percent of the total space, while the other 50 percent was voids filled with air, then the maximum achievable volume reduction ratio would be 2:1. If, on the other hand, the volume of the solid portion of the waste was only 10 percent, and the other 90 percent was air, then the maximum reduction in achievable volume would be 10:1.

Irrespective of the methods used, the limiting condition for volume reduction is the volume of voids in the wastes. Only extremely rigorous methods, such as compression under enormous pressures, could lead to changes in the volume of the solid portion of the wastes. In the absence of changes in the properties of solids, only air or water contained in the voids can be squeezed out.

An important performance criterion of solid waste compactors is the amount of volume reduction they can achieve. Often the performance of a compactor unit is described in terms of a compaction ratio, such as 4:1, 8:1, or 12:1. Such a ratio indicates how much volume reduction is obtained. If the original density is known, the final density can be calculated using this ratio. Unfortunately, solid waste, especially residential solid waste, is highly variable and does not exist at a single density. The components of the waste, the degree of pre-compression, and other factors influence the density of the compressed waste. Thus, the compaction ratio is largely non-descriptive.

There also appears to be considerable confusion with respect to pressures exerted on refuse by compression devices. Many articles stated pressures but did not specifically mention whether the pressure was applied pressure exerted on the refuse or the pressure exerted in the hydraulic cylinder on the ram by the fluid. These pressures vary considerably; the latter is usually many times the former. There are no standard relationships between the two pressures because of different installations and equipment.

Very few references were found concerning the compressibility of solid waste. In addition, no standard tests have been adopted. Several of the ASTM standards have been adopted for other materials and some of the procedures appear to be appropriate for solid waste. ASTM Designation B 331, "Test for Compressibility of Metal Powders" [128], utilizes a compression testing machine capable of applying a total load of 50,000 lbs. and 60,000 psi. The powder (70.0 gms.) is placed into a 1.00-in. diameter die which has been prelubricated with a mixture of zine stearate and methyl chloroform. After applying a preliminary pressure of 5,000 psi, the final pressure of 60,000 psi is applied at a rate not exceeding 60,000 psi per minute. After ejection, the specimen is weighed to the nearest 0.01 gm. and its height and diameter measured to the nearest 0.0005 in. The density of the sample is then calculated.

ASTM Designation D 2213, "Test for Compressibility of Leather" [129], defines the compressibility of leather as the percentage change in the initial thickness of the specimen after being subjected to a pressure of 3,000 ± 100 psi for 3 minutes. The leather samples (2 in. x 2 in. ± 1/32 in.) are placed between two steel plates and the pressure is then applied at the rate of 200 psi per second. The initial and final thicknesses are determined by averaging four measurements of each.

The compactibility of soil is obtained by the Proctor Compaction Test [23,99]. This impact or dynamic test is normally used to arrive at optimum moisture content for obtaining the maximum dry density when compacting soils. It has several variations and is usually used for fine-grained soils (less than No. 4 sieve). It consists of dropping a weight for a fixed number of times on a sample contained in a mold of a given volume (usually 1/30 cu. ft.) and then measuring the weight of the sample used. Molds of 4 to 6 in. in diameter and 4.6 or 5 in. in height are usually used; the samples are placed in the mold in 3 to 5 layers, compacting between layers. The hammer is dropped anywhere from 15 to 55 blows per layer, from either 12 or 18 in. in height. This results in compactive energy of the samples of 7,400 to 56,300 ft.-lb. per cu. ft., depending on the hammer drop distance, the hammer weight, and the mold size. The hammer usually has a 2-in. diameter face and the drops are positioned to insure a uniform distribution of blows on the sample. The resulting wet density may be converted to dry density using the water content of the compacted sample.

A static compression test (Porter Static Test) also is used for unsaturated soils [23]. It consists of applying incremental loads on the soil sample and determining the settlement. The compression loading is usually applied at the rate of 0.1 in. per minute from 100 to 1,000 psi and 0.05 in. per minute from 1,000 to 2,000 psi. The 2,000 psi loading is maintained for one minute and then gradually released. Then the dry weight density of the sample is computed for the various measured heights.

The consolidation test for soil is a long-term compression test [23]. It subjects incremental loading to a soil mass saturated with water (usually clay) and then measures the consolidation or settlement with time. The data from the test make it possible to plot a stress versus volume strain curve. The sample of soil is usually small (about 0.01 cu. ft.), and the compressive force is unidimensional. The load is usually doubled every 24 hours with vertical deflection readings taken between loads. Loads of up to 113.8 psi are usually applied and rebound loads measured.

Di Filippo and Malina [104] used the Proctor compaction test to determine the compaction characteristics for size-reduced waste and several individual components (newspaper, cardboard, magazines, leaves, ash, and wood). The material was dried and ground fine enough to pass through a 6-mm sieve. An automatic tamper was used with the 6 in. diameter and

8-1/2 in. deep Proctor cylinder. A set number of blows was imparted to the samples by a 10-lb. hammer over a 1-1/2 ft. drop. The sample was leveled and its height determined by a depth gage. Several readings were taken on the sample height. An additional compactive effort was applied to the sample by additional blows and the height again determined. The material was weighed after compaction.

The levels of compactive effort at which heights of sample were determined were 25, 50, 100, 200, 300, and 400 blows for a compaction energy effort varying from 4,750 to 253,170 ft.-lbs. per cu. yd. of compacted volume. Twenty-five blows were chosen as the lowest compactive level since the samples were too flexible to accurately obtain a height measurement at lower levels.

The results for the compaction of size-reduced composite and several components are shown in Figure 21. The investigators also found moisture content did not affect the final dry density of the composite compacted samples. In compaction tests at 100 blows, the dry densities of all individual components (except wood) constituted 80 percent or more of the composite dry density.

Moulton [130,131] evaluated the compaction characteristics of various artificial refuse mixtures, using the paper content as the major variable. An impact loading was developed by using a 5.4-lb. hammer with a 12-in. fall and a 6-in. diameter Proctor compaction cylinder. His results for various paper contents are provided in Figure 22. The maximum

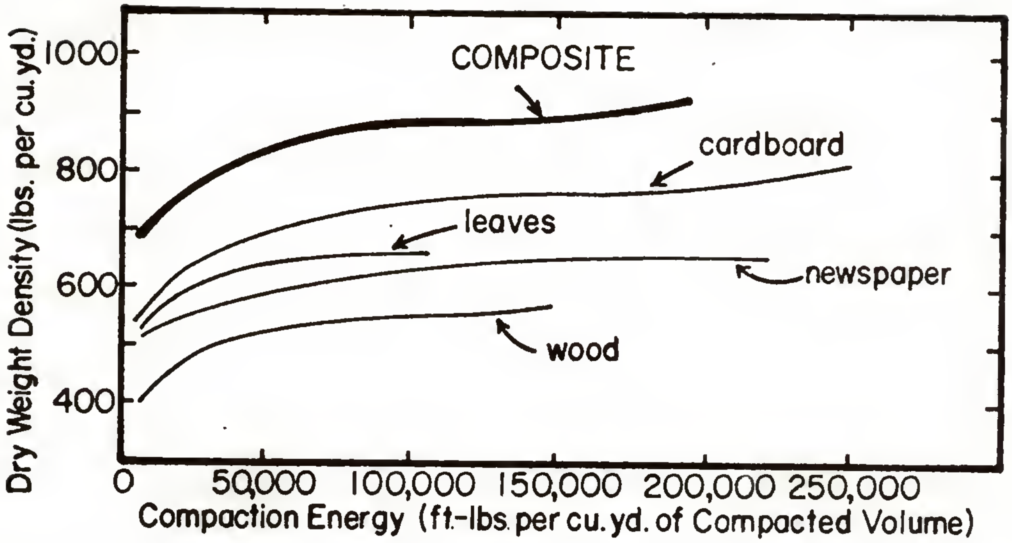

Figure 21. Compaction of size reduced waste at Texas [104].

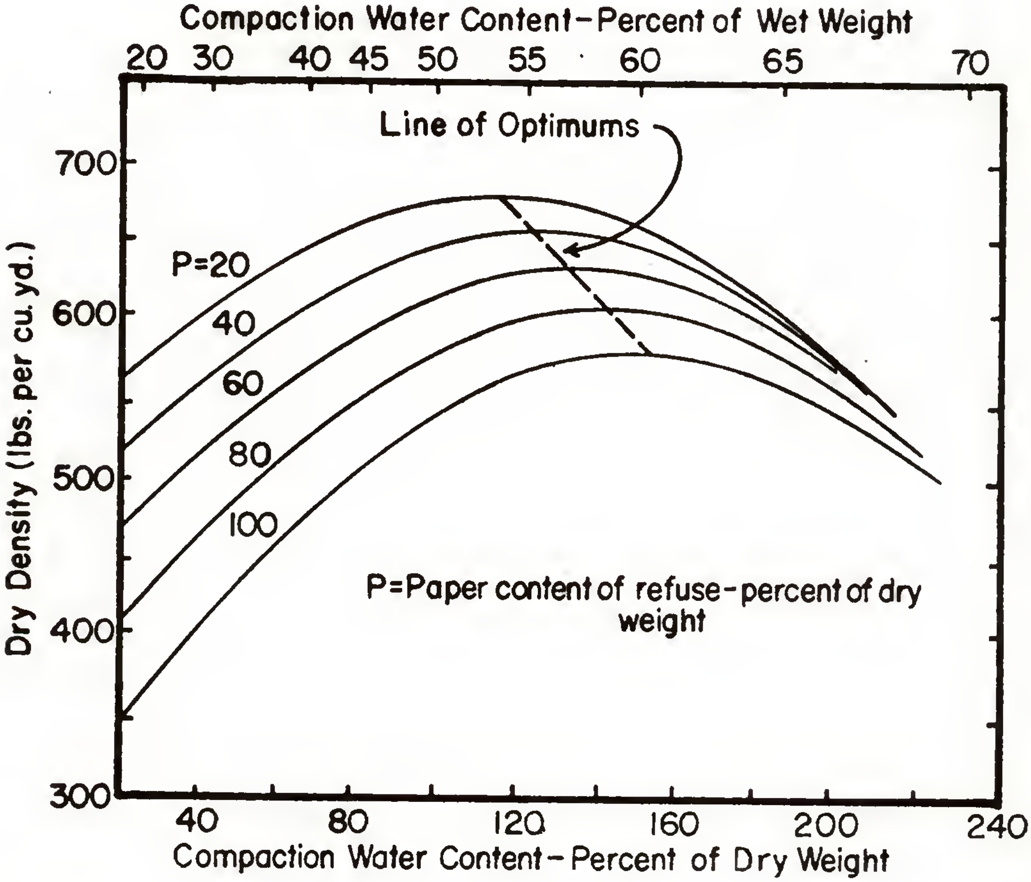

Figure 22. Compaction of artificial waste at West Virginia [131].

density obtained was at a moisture content (wet weight) of 53 to 62 percent. The densities of the refuse mixtures were found to vary inversely with increasing paper content.

Researchers used 55-gallon drums (each 22 in. ID, 34 in. height and 7.45 cu. ft. volume) at Sulfur Springs, Texas, to obtain the compressibility of shredded waste [53]. Milled refuse samples were randomly chosen and the drums filled to the top, bouncing them periodically to assure settlement of the material. The total weight of the material was recorded. A circular board was cut to a diameter of 1 in. less than the inside diameter of the drums, and placed on top of the refuse. The initial starting point was then recorded (depth). Weights were added to the top of the board until the refuse reached equilibrium. The method of determining the equilibrium was not mentioned in the text. The total applied pressures were 0, 0.52, 0.71, 1.23 and 1.79 psi. The distance which the column height had compressed was measured. The rebound of the material was obtained by removing the load and measuring the height of the board at two time intervals, immediately after removal of the load and five minutes later.

The milled samples were prepared as previously described. The results of the compression data are provided in Figure 23. There was no noticeable rebound for any of the samples at either zero or the five-minute reading. One shortcoming of this research was that the barrels were not smooth-walled and therefore the density values were affected accordingly (lower); thus, any possible rebound would be reduced.

Figure 23. Legend:

(1) Compactor trucks - raw refuse (point).

(2) Landfilled by a bulldozer - raw refuse (point).

(3) Landfilled by a bulldozer - shredded waste (point).

(4) Landfilled by a landfill compactor - raw refuse (point).

(5) Home compactors (point).

(6) Low pressure balers - raw refuse (point).

(7) Low pressure balers - shredded refuse (point).

(8) High pressure balers - raw refuse (point).

(9) PHS study at Chandler, Arizona, on raw refuse [4,74].

(10) Study at Walbrook Wharf, London, Great Britain, on raw refuse [74].

(11) Study at Sulfur Springs, Texas, on raw refuse [53].

(12) APWA study at Chicago, Illinois, for raw refuse [107,113].

(13) American Baler Co. study on shredded refuse [106].

(14) Study on raw refuse by Higginson [7].

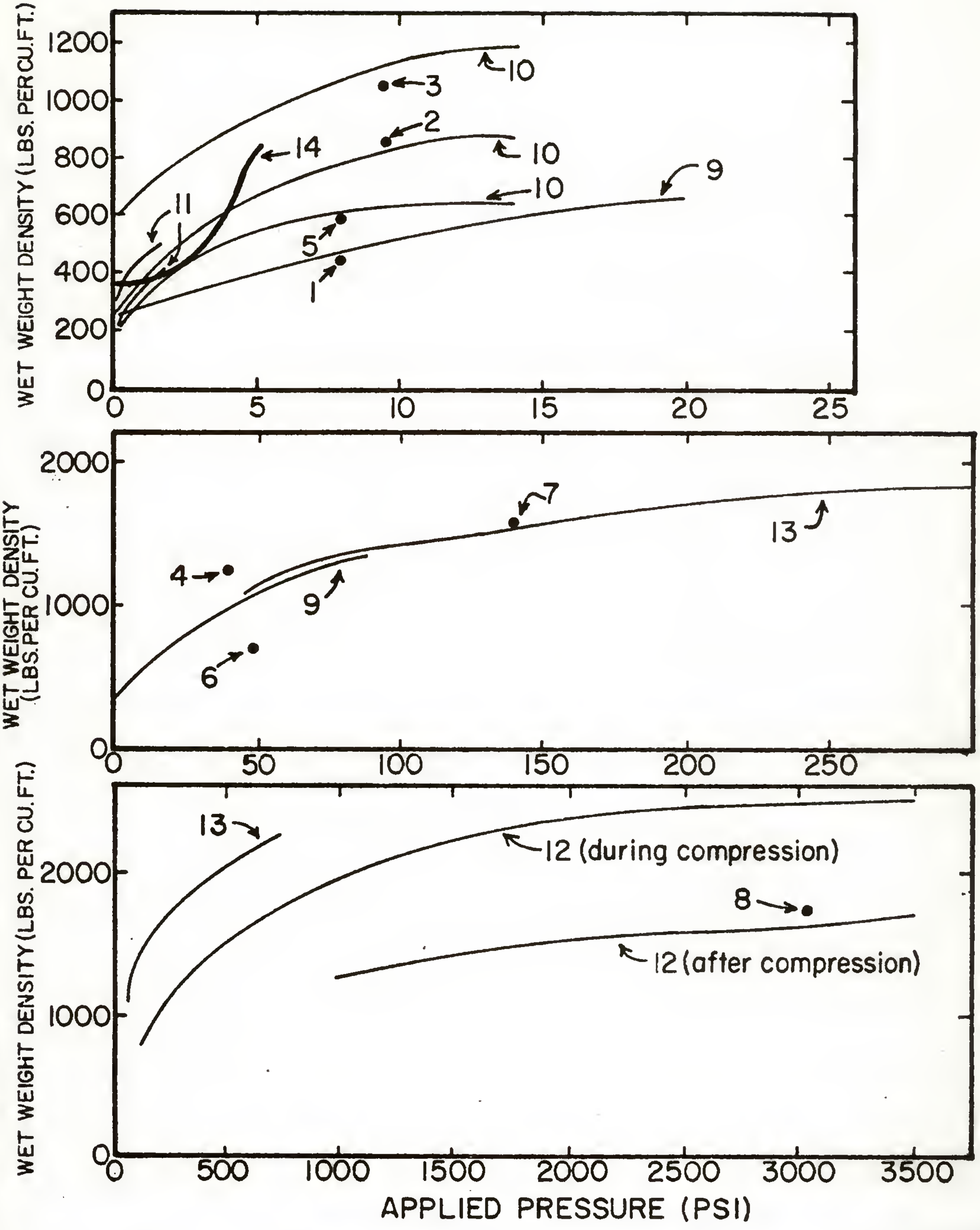

Figure 23. Compressibility of solid waste.

A test of refuse compressibility was made in 1954 by the U.S. Public Health Service at Chandler, Arizona [4,74]. Household refuse was subjected to increasing compressive loads and its density measured. The results are shown in Figure 23. However, the details of the methods were not provided.

The compressibility of refuse in barges at the London Walbrook Wharf was obtained utilizing an overhead foot-type compacting machine [74]. Again, details were not provided. A plot of percent reduction in volume versus applied compressive pressure was provided in the reference for refuse of three initial densities. These data, replotted to provide compressive force versus density, are shown in Figure 23.

A series of compression experiments were done by APWA utilizing several balers, including a large three-stroke hydraulically operated high compaction metal baler [69,70, 107,113]. The purpose of the first two rams of the latter press was to gather refuse from a large charging box into a more confined space of about 7 to 8 cu. ft. The maximum possible pressure exerted by these two rams was 94 and 573 psi, respectively. The final compression of the refuse was accomplished by a third ram which could exert pressures up to 3,500 psi. The pressures applied to the raw waste during the testing period varied from 500 to 3,500 psi; the time required to bale the refuse was approximately 17 seconds. In each compression test, the applied pressure and location of the third ram was continuously recorded during the entire ram travel. The bales were each 20 in. x 16 in. with variable lengths; they were not tied. The results for residential waste both during and after compaction (after 1-2 minutes) are plotted in Figure 23. APWA concluded the magnitude of pressure needed for suitable baling was in the vicinity of 2,500 psi. An increase in pressure above this level did not produce any appreciable increase in density.

APWA found the volume reduction of loose residential refuse of similar density averaged about 13:1 at an applied pressure of 3,000 to 3,500 psi and it decreased systematically to about 9:1 at about 900 psi. The volume reduction ratio was found to be higher for low density refuse and vice versa, irrespective of the applied pressures. The volume reduction ratio of different types of refuse subjected to the same pressure was found to vary from 7:1 to 23:1. The 7:1 value was for waste having a high dirt content. Normal variations were 8:1 to 18:1. APWA also observed the theory of consolidation where larger densities were obtained when the applied pressures were retained.

APWA concluded shredding of refuse prior to compression, as compared to direct baling, neither aided the compression process, nor contributed to the stability of the bale.[1] Researchers found when separate portions of solid waste were compressed in increments, poor compression resulted at the interface of each compressed portion.

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[1] Apparently, the very high pressure which this baler exerted was sufficient to fracture and bend the particles, regardless of the particle size.

The American Baler Company [106] has assembled data on the relationship of applied pressure to the density of shredded refuse. However, little information is available on its techniques. Pressures from 0 to 760 psi were applied to the samples. The results are provided in Figure 23.

Higginson [7] discussed the consolidation of refuse inside a deep bin by its own weight over a period of several days. A crane placed the refuse into the bin so it initially was 44.25 ft. thick. The changes in density were measured at various depths; however, the method was not described. The density of the refuse, following ejection from the collection vehicles, was 344 lbs. per cu. yd. After 2.2 days the densities were measured again and the results are plotted in Figure 23. The resulting curve has an unusual shape, since it is convex while all of the other density versus applied pressure curves are concave. Perhaps this discontinuity can be explained by the limited range of pressures.

Measurements were made also with respect to time. The average densities for refuse at 2.1 and 6.6 days were 484 and 589 lbs. per cu. yd., respectively. The tests confirmed a considerable increase in refuse density under static load conditions and with duration of time.

For comparative purposes, the raw and shredded waste data in Table 12 are plotted in Figure 23 as points data. Average densities and pressures were used for these data.

Trezek, Howard, and Savage [132] studied some compression properties of various raw refuse components (steel and aluminum cans, cardboard cartons, boxes, plastic and glass bottles) using two types of tests. One consisted of measuring and comparing the stress-strain characteristics of samples. Of particular interest in this phase of study were the values of ultimate strength, ultimate strain, and specific rupture energy under various strain rates. The second type of tests performed was concerned with the energy required to effect various degrees of volume reduction in containers constructed of the various materials according to the configurations typically found in municipal refuse. Essentially, the energy tests were of two types: (1) volume reduction of the containers under the action of a steady compression rate, and (2) volume reduction by impact.

The steady compression rate tests were performed with a standard universal testing machine. A level cell was used to apply a compression rate of 1.0 in. per minute. A chart was used to record container compression in terms of load as a function of time. The orientation of containers in these tests was as follows: (1) steel and aluminum cans were subjected to separate radial and axial tests; (2) cardboard boxes and cartons were tested in the upright and horizontal position; and (3) glass bottles were tested in steady compression until they fractured. Determination of the area under the curve for load versus volume reduction yielded a relation between energy expenditure and volume reduction.

The volume reduction by impact test directly gave the energy required to effect a given volume reduction. The apparatus consisted of a vertically positioned 4 in. diameter by 3 ft. high steel tube. Glass and metal objects were placed at the bottom end of the tube so that they and the end of the tube rested on a rigid steel base plate. Weights of 15.9, 21.7, 35.4, and 57 lbs. were fitted to the tube allowing them to be dropped vertically down the tube to crush or cause a volume reduction of the objects.

The energy required to effect certain volume reductions is indicated by the curves in Figure 24. In each case there appears to be two distinct slopes for the energy volume curves. The first slope occurs at volume reductions up to 60 to 70 percent. This slope is essentially linear, and represents the initial buckling and folding of the container wall. In the case of glass, the slope prevailed up to a volume of about 35 percent and represents the initial fracture. During this linear portion, the force required to effect a volume reduction is generally constant. It is reasonable to assume that during this phase of volume reduction the greatest part of the energy or input work is directed toward eliminating the large interior voids of the containers, and essentially no plastic deformation occurs.

After the first phase of volume reduction occurs, the amount of subsequent work or energy required for continued volume reduction increases rapidly. Then it is necessary to begin deformation of the container wall materials, causing the slope of the force-compression curves to approach the elastic moduli of the respective materials.

The accuracy of experimental results deserves comment. The ranges of experimental data encountered in the energy-volume reduction experiments are shown in Figure 24. Each band represents the high and low limits as observed between the radial and axial compression tests. The respective data scatter are within each of these bands. The accuracy of the impact experiments was more difficult to establish because the degree by which the energy of the falling mass is transferred to crushing the container could not be precisely determined.

In the steady compression rate tests, the glass bottles had a tendency to break in the areas of stress concentration, such as in the vicinity of the bottle neck and the bottom. Bottles with more complex shapes generally fractured at lower levels of stress. As the glass pieces became smaller, the stress requirements for further crushing increased. The stress requirements for small glass pieces loaded in pure compression were much greater than for pieces subject to tensile stresses, such as bending.

The amount of force required to crush metal cans was affected by the method of load application. The amount depended on both the direction of the application of the force, such as axial or radial compression, and on the shape of the crushing member. Most of the specimens were compressed between large flat plates. A few experiments were performed

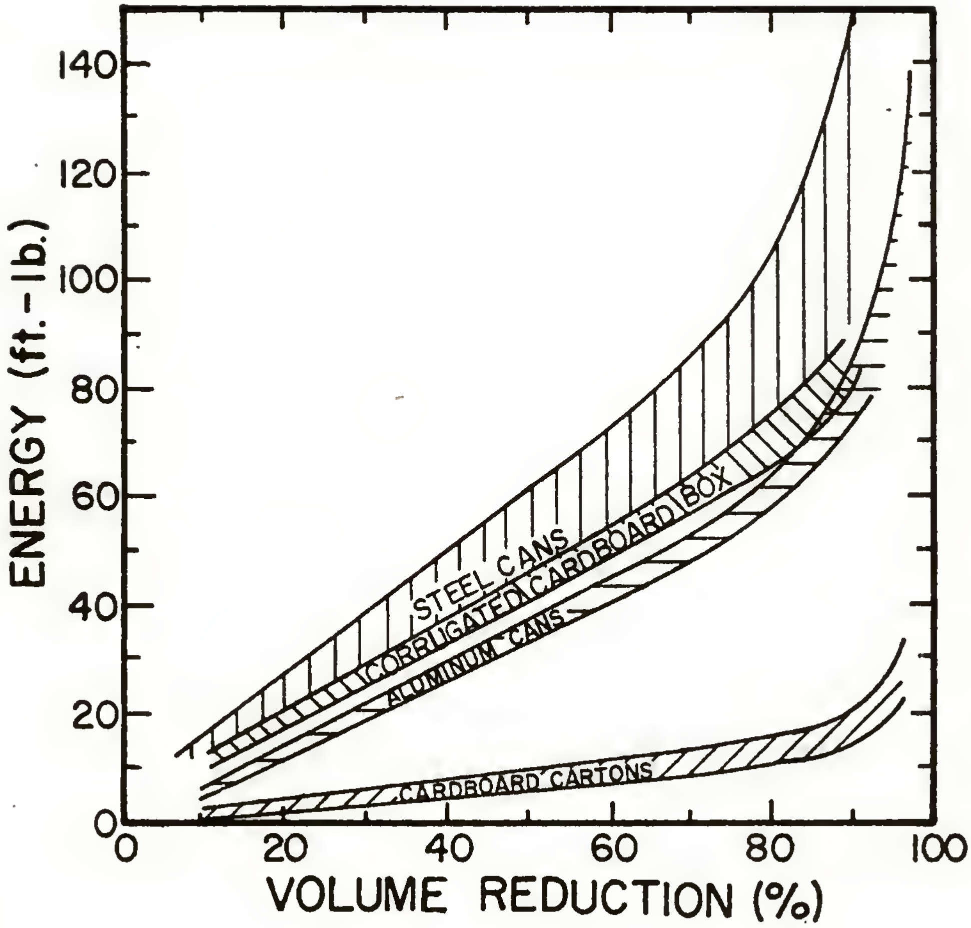


Figure 24. Energy versus volume reduction for several refuse components [117].

in which rods and wedged plates were used as the crushing members. In these cases, even though a considerable variation in the force was observed, the overall energy requirements for a given level of volume reduction had a tendency to approximate values obtained with the use of flat plate crushing members.

Many authors have discussed the springback or rebound tendency of compressed refuse. Refuse has elasticity like other materials and thus will rebound when the pressure is released. The main components responsible for this characteristic are paper, leaves and green twigs. Paper, which is made up of fibers, tends to spring back after release of the applied pressure if the fibers are only bent during the pressure application. Higher pressures or application of pressure for a longer period, however, can weaken the bonds in the bent fibers, reducing the springback [107].

The springback in the APWA study [107], in which high pressure balers were used, occurred rapidly after the pressure was released. Most of the springback occurred within the first two minutes. About 20 percent expansion occurred within 1 or 2 seconds after the pressure was released. The expansion after two minutes was found to be 50 to 60 percent of the original compressed volume.

Expansion continues at a slower rate after the first two minutes. Bales stored individually and permitted to expand without any restriction grew up to 95 percent of their original compressed volume. APWA found the least expansion occurred in the direction of the lowest pressure applications.

Other researchers have experienced rebound after refuse compression. Smith [122] reported that springback was very limited when bales were tied with wire. He reported the rebound at the San Diego baling operation was about 6 percent from the original dimensions of the bales in the extrusion chamber. Also, he found the bales expanded to fill the voids when stacked only a few inches apart. Faülkner [123] reported stacked bales of refuse at St. Paul, Minnesota, expanded during the first three weeks to fill the voids. The bales were stacked only a few inches apart for a 5 percent expansion. Patrick [36] reported the expansion of shredded refuse was considerably less than for raw refuse. Wilson [97] found wetting the refuse reduced the springback.

The stability of bales is an important parameter if the bales are to be transported or handled. APWA [107] found the stability of bales improved at higher compression pressures, after longer periods of pressure application, and when the proper refuse moisture content was provided. Fragile bales (defined as falling apart immediately or after some handling) usually were obtained at pressures of about 500 to 1,000 psi. Bale stability improved at 1,000 to 1,500 psi pressure and showed marked improvement at 2,000 to 3,500 psi. No additional improvement was observed beyond 3,500 psi. The stability of bales at 1,000 to 1,500 psi usually improved appreciably if the pressure was held constant for several minutes. The stability of bales maintained at a compressive pressure of 1,000 psi for 5 minutes was almost equal to those made at 1,500 to 1,750 psi without holding the pressure for any appreciable time. A small quantity of water was found beneficial to the stability of bales made with a high paper content. Large amounts of moisture in high paper content refuse produced bales with poor stability.

Stirrup [125] reported different results than those of APWA. He obtained stable bales prepared at 60 to 80 psi pressure using a screw type vertical box paper baling press. However, at 5,600 psi the high ash content in the refuse kept the bales from holding together. The APWA study [69,70] reported the stability of bales was improved in all cases where the sample contained large proportions of metal.

Experimental Methods and Equipment

Introduction

In order to decide which analytical methods to use, it was first necessary to have some idea of the accuracy and reproducibility of the methods being considered. Unfortunately, very little information was found on this subject in reviewing density and compression methods. ASTM did report on the reproducibility of the test for the compressibility of leather [129]. The relevance of this work is questionable, though, for solid waste because there are many differences between the two materials, the size of the samples and the particles. No information was found on the accuracy and reproducibility of density and compression techniques for solid waste.

The techniques for determining the loose density of solid waste appear to be straightforward. A large container of known size should be utilized. Various size containers have been used for raw refuse, ranging from a 1-cu. yd. wooden box used in Europe [7,18,56] to a 55-gallon drum at Sulfur Springs, Texas [53]. Smaller ones have been used for shredded waste [104]. The sample should be placed into the container in a reproducible manner without compressing the material and then leveled off. The amount of sample used should be weighed and the density calculated.

The compressibility of raw and shredded solid waste appears to be more difficult to obtain. The first decision was whether a static or dynamic impact test would be used. The static test was the method chosen since it more closely resembles the compression methods used in solid waste management (e.g., the compression efforts of landfill equipment, balers and packer trucks), and thus these results could be widely utilized. On the other hand, the Proctor dynamic test, the alternative, produces highly localized pressure for each drop of the hammer and therefore may damage particles such as bottles. In addition, the Proctor test does not provide low pressure results, as it is usually necessary to drop the hammer 15 or more times before the material is compressed uniformly and sufficiently to obtain initial results.

Another advantage of the static test is that the initial results (prior to the application of pressure) are the loose density of the subject sample. Thus, it was decided to determine the compressibility of refuse by the static test using a piston to compress the refuse.

The compression test requires sufficient intermediate results to adequately define the compression curve (pressure versus density). This necessitates intermediate measurements of the location of the piston to obtain the volume of the specimen. It also is desirable to apply pressure to the samples in a uniform manner so that results may be readily compared. This is necessary because refuse is semi-elastic. The duration of load application must be established before determining the location of the piston. The greater the period of pressure application, the greater the resulting density.

It is desirable to obtain some information on the rebound or expansion characteristics of refuse after the applied load is removed. In order to obtain these values, it was necessary several times during testing to unload and reload each sample specimen to a higher pressure.

The size of the compression samples should be as large as possible to overcome problems with the large particles. Larger samples are required for raw refuse than are necessary for shredded waste to obtain the same degree of accuracy and reproducibility. At the same time, there are size constraints because of available equipment, budget limitations and drying oven capacity.

Very little information has been provided on the size of samples in refuse compression studies. Moulton [130,131] used 0.08-cu. ft. samples of size-reduced waste in his Proctor cylinders. The researchers at Sulfur Springs, Texas [53], used 55-gallon sample sizes, but they applied less than 2 psi pressure to the samples. The large size of their samples and limitations of their equipment prevented them from applying greater pressures.

Several investigators used very expensive presses to apply extremely high pressures (up to 5,000 psi) to solid waste samples. It is questionable whether high pressure balers are desirable because most processes in solid waste management compress the refuse to much less than 100 psi pressure (Table 12). Budget limitations prevented the purchase of similar equipment.

Equipment

In acquiring equipment for the density and compression tests, it was desirable to use equipment which could be easily duplicated by other researchers. Thus, equipment was purchased which could be readily obtained on the open market. Although it was necessary to compromise on the size of the press due to the budget and sample preparation constraints, it was felt a compression cylinder one foot in diameter would be sufficient for all of the samples. Some problems might occur with this size cylinder for a few of the larger particles of raw waste. If so, this might require that these particles be omitted or, if possible, reduced in size.

A complete description of the equipment used in the compression test is provided in Appendix D. A photograph of the testing equipment and a cross-sectional diagram of the compression cylinder are provided in Figures 25 and 26, respectively.

A ten-ton capacity laboratory model hydraulic press was purchased from Enerpac of Butler, Wisconsin. The hydraulic cylinder of the press had a 10-1/4 in. stroke and the maximum fluid pressure was 10,000 psi. A 0-to 24,000-lbs. pressure gage with 200-lbs. increments was used to measure the applied load on the refuse. A hydraulic hand pump was used to apply the pressure in the hydraulic cylinder.

Technicians from the Mechanical Engineering Department, University of Florida, constructed the sample cylinder and piston according to the dimensions shown in Figure 26. The inside walls of the steel cylinder were smoothed by turning on a lathe and sanding. The steel piston weighed 70 lbs. and the center was bored and threaded so it could be attached to the ram of the hydraulic cylinder. There was 0.125 in. clearance between the piston and the wall of the compression cylinder.

Several metal plates were used with the press. An 11-13/16 in. diameter x 1/2 in. steel plate was placed in the cylinder (prior to placing the sample) to prevent the sample

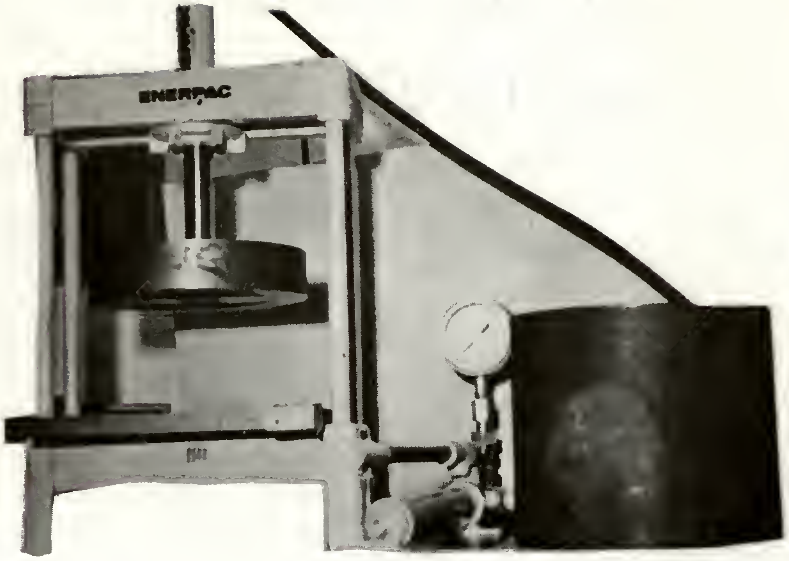


Figure 25. Compression equipment.

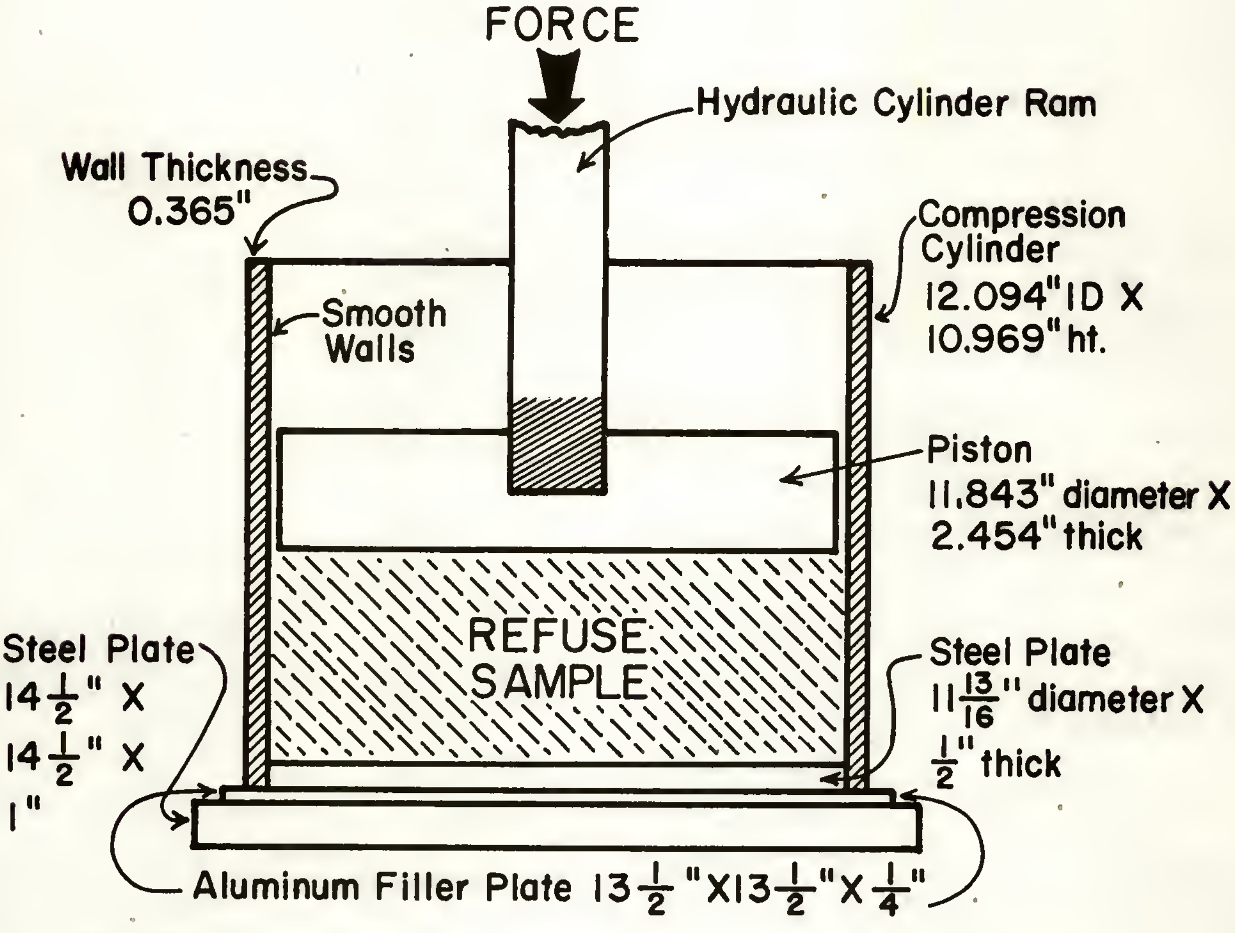

FORCE
Hydraulic Cylinder Ram
Wall Thickness 0.365"
Compression Cylinder 12.094" ID X 10.969" ht.
Smooth Walls
Piston 11.843" diameter X 2.454" thick
REFUSE SAMPLE
Steel Plate 14 1/2" X 14 1/2" X 1"
Steel Plate 11 13/16" diameter X 1/2" thick
Aluminum Filler Plate 13 1/2" X 13 1/2" X 1/4"

Figure 26. Cross-sectional diagram of the compression cylinder.

from escaping during testing, and to prevent bending of the bottom plate. It was necessary to use 1/4 in. thick x 13-1/2 in. square aluminum filler plates for exceptionally compressible materials. This was because the ram of the hydraulic cylinder could only be lowered 10-1/4 in., which allowed the piston to reach within 1.10 in. of the bottom of the sample when filler plates were not used. The filler plates were placed underneath the cylinder to raise it and the samples. Normally, these plates were placed in position prior to the beginning of compression. Occasionally, it was necessary to insert one or two during the testing when the compressibility of the sample was underestimated. Usually this was done during the initial rebound measurements.

The maximum force which could be exerted by the compression testing machine on the sample was 174.1 psi. The weight of the heavy piston exerted an additional force of 0.6 psi. Therefore, the total maximum pressure which could be exerted on the sample was 174.7 psi.

Because the 11-13/16 in. diameter steel circular plate displaced some of the volume of the compression cylinder, a depth of 10.469 in. of the cylinder was available for the refuse. This resulted in an initial sample volume of 0.6960 cu. ft.

Two other items also were used in the compression test. A 7-in. long vernier caliper (with 0.001-in. graduations, inside-outside jaws, and a depth gage) was used to measure the location of the top of the piston. Thus the thickness of the sample could be calculated since the location of the bottom of the sample was known. Silicon spray was used on the inside of the compression cylinder in order to reduce sidewall friction during the compression test.

The loose density of each solid waste sample was determined from the initial results of the compression test (prior to the application of pressure). It was felt the initial results of the compression test were sufficiently accurate for determining the density of most of the samples and new equipment need not be acquired, nor another method developed for this purpose. No problems were expected with this method of determining the loose density of the fine particle materials (shredded waste); some reproducibility problems were expected for the raw refuse.

Analytical Techniques

After collecting the gross samples, they were dried for two to four days at 70 to 75°C. The dried shredded waste samples were carefully quartered and two of the quarters chosen for the compression test. A third quarter was used for the sieve analysis test and the last quarter was held in reserve. Occasionally, the gross sample was of insufficient size to allow quartering and it was necessary to divide it into only two or three fractions. In some cases, size of sample limitations made it necessary to use the reconstructed samples after sieving for the compression test.

The preparation of the raw sample was quite different. It was necessary to wait until the sieve and composition analyses were completed before the compression test was initiated. It was then necessary to reuse the sieve sample for the compression test. The quartering procedure was utilized only for the fractions less than 1 in. Manual sorting was used for the material above 1 in. in size which comprised the large majority of the sample. It was also necessary to remove or reduce in size particles too large for the test equipment (8 to 16 in.). The composition and sieve analyses data were then modified accordingly for use with the compression data. Each quarter was gently mixed after the quartering procedures were completed to insure a uniform sample.

The loose density of each sample was initially determined using the compression test equipment. This consisted of placing the aluminum filler plates on the laboratory table and positioning the compression cylinder on top of them. The circular steel plate was placed into the cylinder and the inside of the compression cylinder sprayed with silicon.

The test sample was placed gently into the compression cylinder in a reproducible manner, being careful not to compress the material. Particles were not allowed to drop more than 1 in. Sufficient material was added to fill the cylinder. This was determined by placing a straight-edge on top of the cylinder and placing additional material in the voids at the surface until the volume of the indentations (below the straight-edge) was approximately equal to the volume of the material protruding above the straight-edge. The straight-edge was repositioned several times on top of the cylinder to insure the entire surface of the sample was covered. The weight of each sample was determined to the nearest 0.1 gm. with the Ohaus scale. Each quarter sample was weighed initially and after the material was removed for placing in the cylinder. The difference of these weights gave the size of test samples, shown in Table 15. Many of the 79 samples analyzed were replications.

Table 15

Sizes of Density and Compression Test Samples

Type of Sample	Weight of Test Samples (lbs.)			Number of Test Samples
	Minimum	Mean	Maximum	
Raw (R)	1.003	2.561	4.448	22
Primary (P)	1.071	2.325	3.635	23
Secondary (S)	1.541	3.407	5.528	25
Rasp (J)	5.930	6.663	7.985	9
Total	1.003	3.228	7.985	79

The compression test followed the loose density determination. The compression cylinder, plates, and sample were placed directly under the steel piston of the press and the cylinder shifted until the piston was centered. The initial time was recorded and the test started. The test consisted of lowering the piston into the cylinder (utilizing the hydraulic hand pump) and exerting a pressure on the sample. The force exerted on the piston was read directly from the pressure gage. It was necessary to add 70 lbs. force to the gage reading (due to the weight of the heavy piston) in order to obtain the force applied to the sample.

The test consisted of incrementally applying increased pressures to the refuse sample and immediately measuring the location of the top of the piston. This value was then used to determine the depth and corresponding volume of the compressed sample. The compressed density was obtained by dividing the sample weight (lbs.) by the volume of the compressed sample (cu. yd.).

Forty-seven different pressures (from 0 to 174.7 psi) were applied to each sample in increasing order. With the exception of a few tests, each sample received the same loading schedule. This schedule is shown on the "Density and Compression Test Data Forms," a copy of which is found in Appendix G. The data for Sample 101 (P-11) are recorded on this form and calculations shown to illustrate the procedures used. Initially, pressure readings were made at every 100 lbs. With increasing loads, the readings were increased to every 200, 400, 500 and then every 1,000 lbs., to the capacity of the press (20,000 lbs.). Depth gage readings were taken at every pressure reading. It usually took about 10 seconds to obtain a depth gage reading after each respective pressure was reached. The total testing time for each sample averaged 29.3 minutes.

The lowest pressure that could be applied to the sample from the hydraulic system and piston was 4.1 psi. In order to obtain a reading at a lower pressure, it was decided to exert a pressure on the sample by the weight of the piston only (0.7 psi). This was accomplished by lowering the piston with the hydraulic hand pump until the only pressure exerted on the sample was the weight of the piston. Then the piston was unscrewed from the hydraulic cylinder ram and two diametrically opposite depth readings measured at the top of the piston. These values were averaged and recorded.

The expansion characteristics of the compressed refuse, when the load was released, were determined by evaluating three rebound tests. The rebounds were determined after the loads of 5.0, 10.2, and 174.7 psi were reached. They were accomplished by releasing the pressure until the ram could be unscrewed from the piston. This was done and the location of the top of the piston measured at two diametrically opposite points. These values were taken about one minute after the rebound was started and then recorded as the average of the two readings. The rebound was not completely released to zero pressure. This was basically because the top of the compressed refuse was still uneven, thus making it difficult to obtain accurate depth gage readings. It also was done for convenience since once the compression test began it was very difficult to remove the piston from the cylinder without dismantling the test equipment. A double-acting hydraulic cylinder would have been useful in this case.

The vernier caliper was used to measure the location of the top of the piston throughout the compression test and readings were recorded to the nearest 0.001 in. The limited length of the caliper made it necessary to utilize three different measuring techniques (A, B, and C), depending on the location of the piston (or the compressibility of the waste). Method A was used when the top of the piston was above the top of the cylinder. This was done by placing the end of the depth gage on the edge and perpendicular to the piston and extending the depth gage downward until it touched the top of the cylinder. The vernier was then read and recorded. The depth of refuse was calculated by adding 8.014 in. to the reading. This method of measuring was seldom used.

Method B was used when the top of the piston was located from 0 to 4.9 in. below the top of the cylinder. This measurement was obtained by placing the end of the caliper on the edge of the cylinder perpendicular to the top of the compression cylinder and extending the depth gage until it touched the top of the piston. The vernier reading was recorded and the depth of refuse obtained by subtracting this value from 8.015 in.

The last method, or Method C, which measured the distance from the bottom of the press beam to the top of the piston, was the most frequently used. It was used when the top of the piston was more than 4.9 in. below the top of the cylinder. Measurements were taken by placing the top inside jaw of the caliper under the bottom of the beam, adjusting the caliper until it was vertical, and extending the depth gage downward until it touched the top of the piston. The depth of refuse was calculated by subtracting the vernier reading from several constants whose values depended on the thickness of aluminum filler plates used.

CHAPTER V

EXPERIMENTAL RESULTS - PARTICLE SIZE ANALYSIS

Introduction

Large masses of numerical data were collected and analyzed. The initial step necessary in analysis of the data was to assess its nature and uncertainty. Unorganized lists of numbers representing the results of the experiment are not easily assimilated. Therefore, it was necessary to use various data reduction techniques to facilitate interpretation and evaluation, and more efficient presentation of the results.

Particle size determinations are almost always undertaken to obtain information about the size characteristics of very large numbers of particles. Since the particles which are studied in a group rarely have the same size, information is needed concerning both the average particle size and the scatter of sizes about the average. The size of a large number of particles must be measured and the data statistically analyzed and arranged so that the size distribution is apparent.

A basic physical property common to all samples is the particle size distribution, that is, the frequency of occurrence of particles of every size present. The characteristics of a single particle are not usually of practical interest;

rather, the mean characteristics of a large number of particles should be studied statistically. The result obtained from particle size measurements is the probability that a given particle picked at random has a specified size or frequency of occurrence. The frequency of occurrence may be reported as the number of particles or a weight greater (or smaller) than a stated size or range of sizes. When the frequency of occurrence of particle sizes is determined by number, a number-size distribution is obtained. Weight-size distributions are obtained when size frequencies are measured on a weight basis. Size-frequency measurements made by sieving represent weight-size distributions [2,24-26].

Analytical Techniques

The analytical techniques of sieving and classification were straightforward and did not present significant problems. A clear-cut separation was obtained with the screens. The only negative aspects of the analysis were that it was relatively noisy and an appreciable amount of air-borne dust was produced with waste of high dust content. The weight loss due to the dust problem must not have been significant, however, since very few of the samples lost weight during sieving. In fact, all except three of the 63 analyses gained weight. A summary of the difference in weights between the test samples and the sum of the sieve fractions is provided in Table 16.

Table 16

Summary of Difference in Weights of Sieve Test Samples and Sum of Sieve Fractions

Type of Sample	Average Difference (Percent of Test Sample)	Range (Percent of Test Sample)
Raw	0.96	0.38-2.75
Primary	1.42	0.02-2.60
Secondary	1.10	0.03-1.76
Rasp	0.38	0.09-1.11

Many of the deviations exceeded the proposed 1.2 percent weighing error tolerance. The deviations still existed after the samples were rechecked for possible analytical errors. Obviously, the samples were absorbing moisture from the atmosphere, although the room was dehumidified. Since it was unreasonable to correct this error, the same analytical procedures were followed. The sum of the sieve fractions was used as the total sample weight in subsequent calculations instead of the test sample weight.

Due to the numerous particles in the fine sieve fractions, it was necessary to take subsamples from those fractions greater than No. 30 sieve to estimate their composition. Obviously, the size of each subsample varied with the size of the sieve fraction, i.e., samples with large particle sizes required large subsamples. In order to determine the size of each subsample, an experiment was run on the No. 4 to 3/8-in.

sieve fraction of Sample S-7. It was decided to divide this fraction in half and randomly choose one of the halves. This procedure was consecutively repeated on each randomly chosen half, thus sequentially obtaining samples 1/2, 1/4, 1/8, . . ., 1/256 of the original size, as shown in Figure 27. This resulted in nine separate fractions, including two fractions of 1/256th in size.

Then the fractions were classified into components and both the number of particles and weight of each component were measured. The combination of the two 1/256 fractions formed a 1/128 fraction; thus each 1/256 fraction became a subsample of the combined 1/128 fraction. This subsample was used to estimate a parameter for the larger fraction. Similarly, the combination of the two 1/256 fractions plus the 1/128 fraction formed a 1/64 fraction. Each 1/128 fraction was then used to estimate the larger 1/64 fraction.

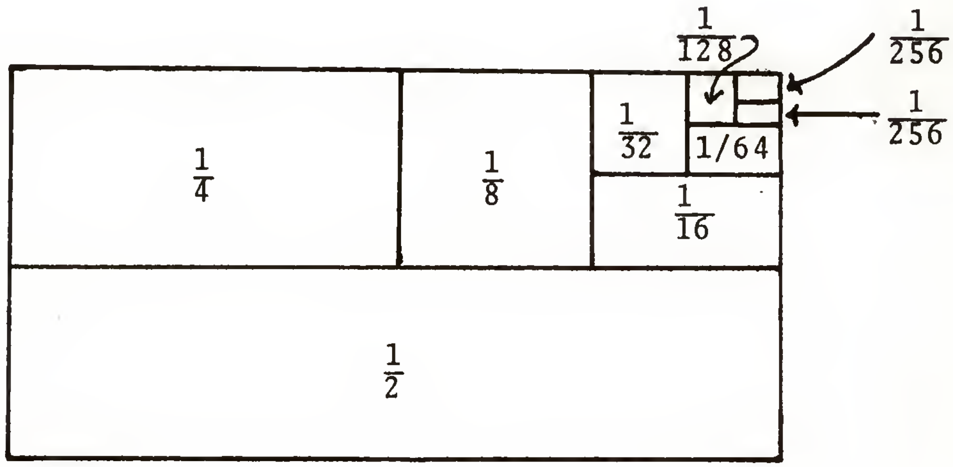


Figure 27. Schematic of subsampling procedure.

In like manner, each smaller fraction was used to estimate the larger fraction of which it was a subset. The total fraction was then considered the population and each subsample, an estimate of the population. This procedure was applied to each component of each subfraction. The results are presented in Table 17.

An example of the increased accuracy by estimating with larger samples can be shown with the paper component. A paper composition of 65.10 percent was found in the total fraction (population). This value was estimated with subsamples. An estimate of 48.9 percent was obtained with the smallest subsample (1/256), considerably less than the true value. Increased accuracies were obtained with larger subsamples, as evidenced by the data. Close values were obtained with 1/16 or larger subsamples. Similar results were obtained with other components.

The criterion followed was that the subsampling procedures should have sufficient accuracy to estimate within 5 percent of the total weight for each component. This was accomplished by the 20 gm. and larger subsamples. Thus, a subsample size of 20 gm. or larger was decided for the No. 4 to 3/8-in. sieve fraction.

The accuracy of estimation did not depend on the size of the original population, but it did depend on the size of the sample and the diameter of the particles. Specifically, it depended on the number of particles in the subsample. It was found that a subsample of 20 gm. or 971 particles was required

Table 17

Estimation of Population by Subsamples

Component	Subsample Composition (dry weight percent)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Food	4.5	2.1	0.9	10.3	7.2	5.8	3.5	2.9	1.82
Garden	4.4	2.1	1.9	1.3	1.8	1.0	1.2	1.4	1.96
Cardboard	42.2	43.2	28.6	17.1	16.0	19.7	19.8	22.1	22.44
Paper	48.9	52.6	66.7	53.1	64.2	63.2	64.2	65.8	65.10
Plastic, etc.	--	--	1.9	2.9	1.7	1.2	2.0	1.4	2.47
Textiles	--	--	--	--	--	--	--	--	0.06
Wood and limbs	--	--	--	--	--	0.9	0.5	1.2	2.40
Ferrous	--	--	--	--	--	--	1.0	0.5	0.22
Non-ferrous	--	--	--	--	--	--	--	--	0.16
Glass, etc.	--	--	--	8.8	5.2	6.2	6.2	3.8	2.88
Rock and gravel	--	--	--	6.5	3.9	2.0	1.6	0.9	0.49
Ash, etc.	--	--	--	--	--	--	--	--	0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.00
Size of subsample (fraction of total)	1/256	1/128	1/64	1/32	1/16	1/8	1/4	1/2	Population
Size of subsample (grams)	0.45	0.95	2.13	6.14	10.32	20.11	39.91	71.45	172.6
Number of particles	34	67	123	241	481	971	1744	4357	7758

for the No. 4 to 3/8-in. sieve fraction. Accordingly, a similar number of particles would be required for subsamples of smaller particles.

The weight of the smaller particle subsamples can be determined theoretically by using the relationship:

$$W_x = f(d_x^3) \tag{12}$$

where W_x = weight of sieve fraction x, and

d_x = the particle diameter of sieve fraction x.

This relationship is detailed in Table 18.

Table 18

Recommended Subsample Weights for Various Sieve Fractions

Sieve Fraction Number	Sieve Fraction	Average Particle Size-d_x (in.)	d_x/d_5	$(d_x/d_5)^3$	Recommended Subsample (gm.)
2	No.30-No.16	0.0352	0.1255	0.0020	0.04
3	No.16-No.8	0.0703	0.250	0.016	0.31
4	No.8-No.4	0.1404	0.500	0.125	2.50
5	No.4-3/8 in.	0.281	1.0	1.0	20

Since 20 gm. were adequate for the No. 4 to 3/8-in. fraction, the size of the smaller particle fractions would then be in proportion to the cube of their diameters. Thus, the last column represents 20 gm. multiplied by the fifth column.

In reality, much larger subsamples were used, as shown in Table 19. The actual samples used were approximately four times greater in size than recommended. In addition, it was unnecessary to take subsamples of many of the No. 8 or greater fractions, when the complete fractions (population) were analyzed. Consequently, the accuracy of estimating the composition was much greater than the 5 percent tolerance.

Table 19

Size of Subsamples Used

Sieve Fraction	Recommended Subsample Size (gm.)	Average Subsample Size (gm.)	Range of Subsample Sizes (gm.)	Number of Subsamples
No.30-No.16	0.04	0.2020	0.0771-1.1043	63
No.16-No.8	0.31	1.1200	0.6331-3.01	61
No.8-No.4	2.50	10.722	5.05-116.0	47
No.4-3/8 in.	20	67.61	40.9-187.4	32

Time measurements also were made during the classification process. The time was recorded for classifying each fraction or subfraction. These figures have been averaged and the results are as follows:

Sieve Fraction	Average Classification Time-minutes
0-No.30	37.5
No.30-No.16	65.0
No.16-No.8	97.5

(continued)

Sieve Fraction	Average Classification Time-minutes
No.8-No.4	115.0
No.4-No.3/8	53.8
3/8 in.-1/2 in.	35.6
1/2 in.-3/4 in.	28.6
3/4 in.-1 in.	15.0
1 in-2 in.	15.0
2 in.-4 in.	12.8
4 in.-8 in.	5.0
Total	480.8

The total time required for classification of one sample was about 8 hours. An additional two hours were required to sieve the samples.

Frequency Distributions

Sieving inherently classifies particles into various class sizes as measured by weight. The particles in this research were classified into a maximum of 12 different classes depending on the size range of particles for each sample. Thus, frequency distributions were directly obtained from the sieve analysis data.

The classification data also represented individual frequency distributions, multiplying the total number of such distributions by the number of separate categories. An example of sieve frequency distributions is found in Appendix E for Sample No. P-11. Fourteen separate frequency distributions (13 components and the composite) are provided in this data sheet. The rows of this array represent the component and composite distributions, while the columns represent the sieve fractions or classes.

Some 63 different arrays were obtained in this research. The rows and columns of each were summed to provide the total weight in grams of each sieve fraction and each component, respectively. The values were then divided by the total sample weight and multiplied by 100 to provide percentages. Thus, the sum of the rows represent the percent composition for each component and the sum of the columns represent the composite sieve fractions. The latter also was a relative frequency distribution.

After reviewing the data, it was concluded that the rock and gravel category should be combined with the ash, earth, and sand category. This decision was made because the results indicated distinct common distributions would be obtained with their sum. In addition, it became evident that it was rather arbitrary to define the limits of both of these categories by the No. 8 sieve. Thus, these two categories were combined to form a new category, titled "Sand and Rock."

It was necessary to average the results from several test samples since they were not independent samples. In order to obtain the variability of "twin samples," 8 gross samples (4 primary and 4 secondary) were physically divided, resulting in additional test samples. Each test sample was then analyzed separately. The variability results will be presented later in this chapter. The array values (percentages) of each "twin sample" were averaged in order to form independent results.

Each independent sample was used to estimate its respective population, e.g., the 14 primary test samples were used to estimate the primary population. This was done for each value of the array including the composition and the composite sieve fractions. The results were averaged and the variance and coefficient of variation determined. The composition, range of particles, and the weighted coefficients of variations (the sum of the products of the coefficients of variation multiplied by their respective class widths) are provided in Appendix H for each population.

Standard numerical and graphical techniques were used to display the results. An example of these techniques can be demonstrated using the paper component of the raw waste population. Similar techniques also were used for the other components and the composite for this and the other populations.

The paper component of the raw waste data is displayed in Table 20 and also provides a frequency table. The screen data in this table were directly obtained from Table 5. The data were arranged in 12 classes of increasing sizes. All observations belonging to a given class were assumed to coincide at the class midpoint.

Table 20

Frequency Distribution of Paper Component of Raw Waste

Class Number (i)	Class Boundaries (in.)	Class Width (in.)	Class Midpoint (in.)	Frequency (by weight)		
				(%)	(%)	(%/in.)
1	0-0.0234	0.0234	0.0117	0.02	0.05	1.71
2	0.0234-0.0469	0.0235	0.0352	0	0.01	0.10
3	0.0469-0.0937	0.0468	0.0703	0	0.01	0.10
4	0.0937-0.1875	0.0938	0.1406	0	0.01	0.08
5	0.1875-0.375	0.1875	0.281	0.10	0.21	1.10
6	0.375-0.500	0.125	0.438	0.05	0.10	0.80
7	0.500-0.750	0.250	0.625	0.10	0.19	0.76
8	0.750-1.00	0.250	0.875	0.23	0.45	1.82
9	1.00-2.00	1.00	1.50	2.21	4.35	4.35
10	2.00-4.00	2.00	3.00	10.82	21.34	10.67
11	4.00-8.00	4.00	6.00	30.40	59.96	14.99
12	8.00-16.00	8.00	12.00	6.76	13.33	1.67
Total				50.69	100.0	

The relative frequency distribution of this component was obtained by dividing each class frequency by the total frequency of all classes, and then expressing the results as a percent. For example, the relative frequency was obtained by dividing each value in the fifth column by 50.69, the percent composition. The results are shown in the sixth column. The sum of the classes of a relative frequency distribution totals 100 percent.

The graphical representation of the relative frequency data is presented in the histogram in Figure 28. The areas of the rectangles of a histogram are proportional to the class frequencies. Thus, for class widths of equal sizes, the heights of the rectangles are numerically equal to the class frequency values. If the class widths do not have equal sizes (as normally found for sieve results), the heights must be adjusted since the rectangular areas are proportional to the class frequency. This was easily accomplished by dividing the class frequency by the class width, obtaining frequency per inch for each class, as indicated in the last column of Table 20. It is possible to have frequency values exceeding 100 percent per inch with unequal classes [2,24,133].

The data in Table 20 also have been plotted (with data points indicated) as a frequency curve, often called a probability distribution curve (Figure 28). Areas under this curve are associated with probabilities. For example, the total area is 100 percent, which infers all particles fall between the range of 0 and 16 in. The probability of particles falling between any other range within 0 and 16 in. may be directly obtained by calculating the respective area under the curve.

The probability distributions for the composite waste are shown in Figures 29-32. The range of values for each sample is indicated on these figures. The probability distribution curves for the components are provided in Appendix I. These latter distributions were obtained from mathematical

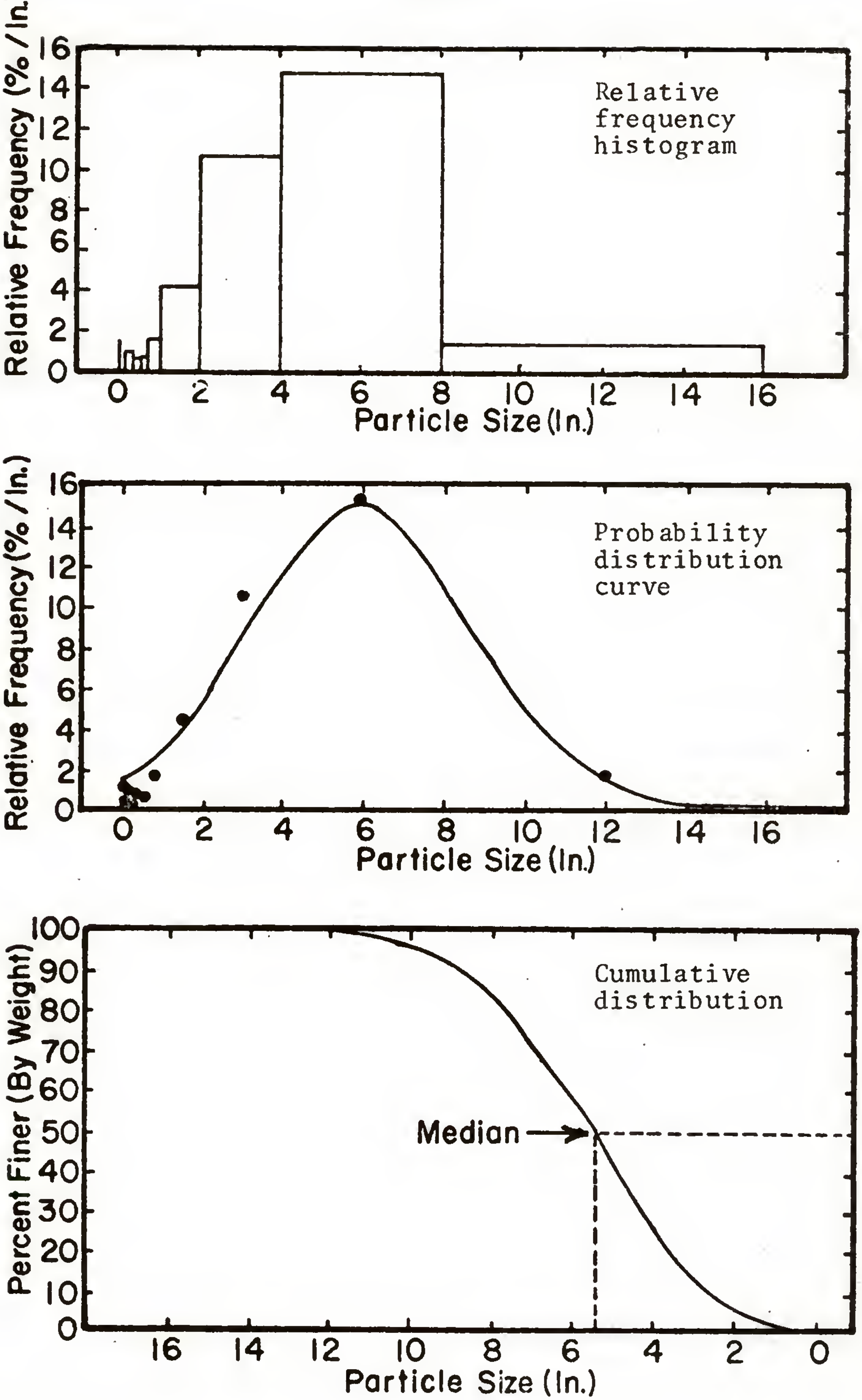


Figure 28. Frequency distributions of paper component of raw waste.

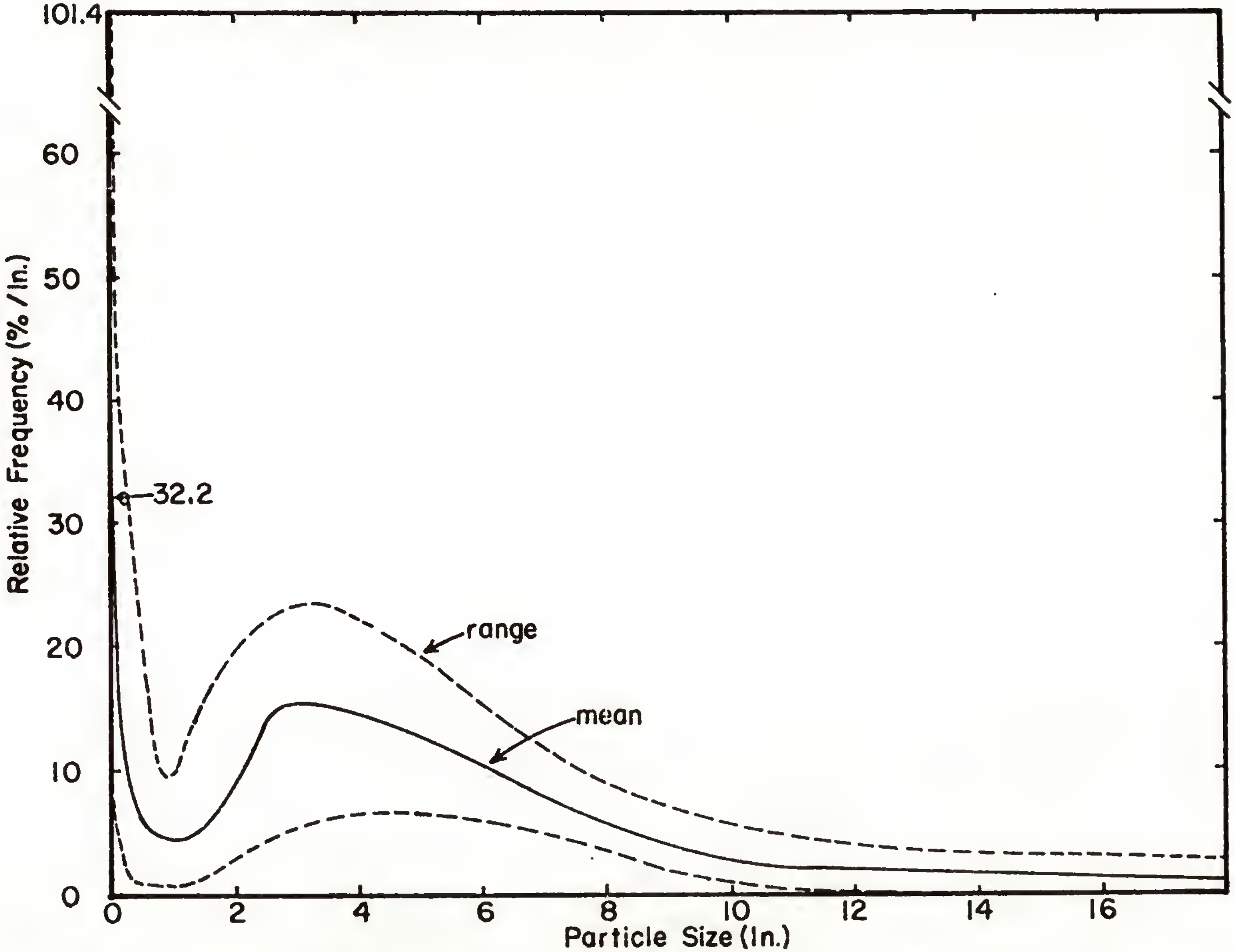


Figure 29. Particle size distribution of raw waste from Gainesville, Florida.

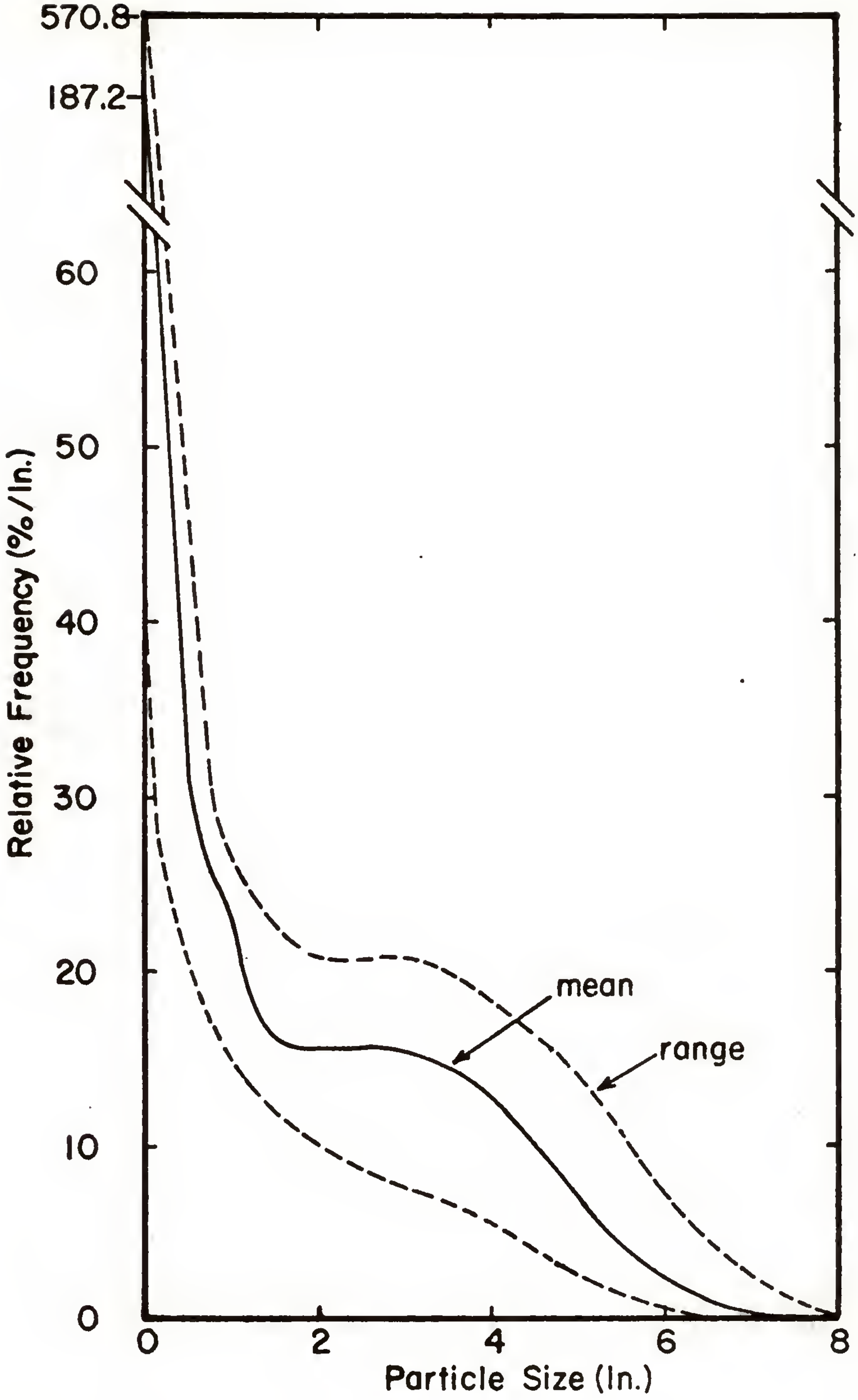


Figure 30. Particle size frequency distribution of primary shredded waste from Gainesville, Florida.

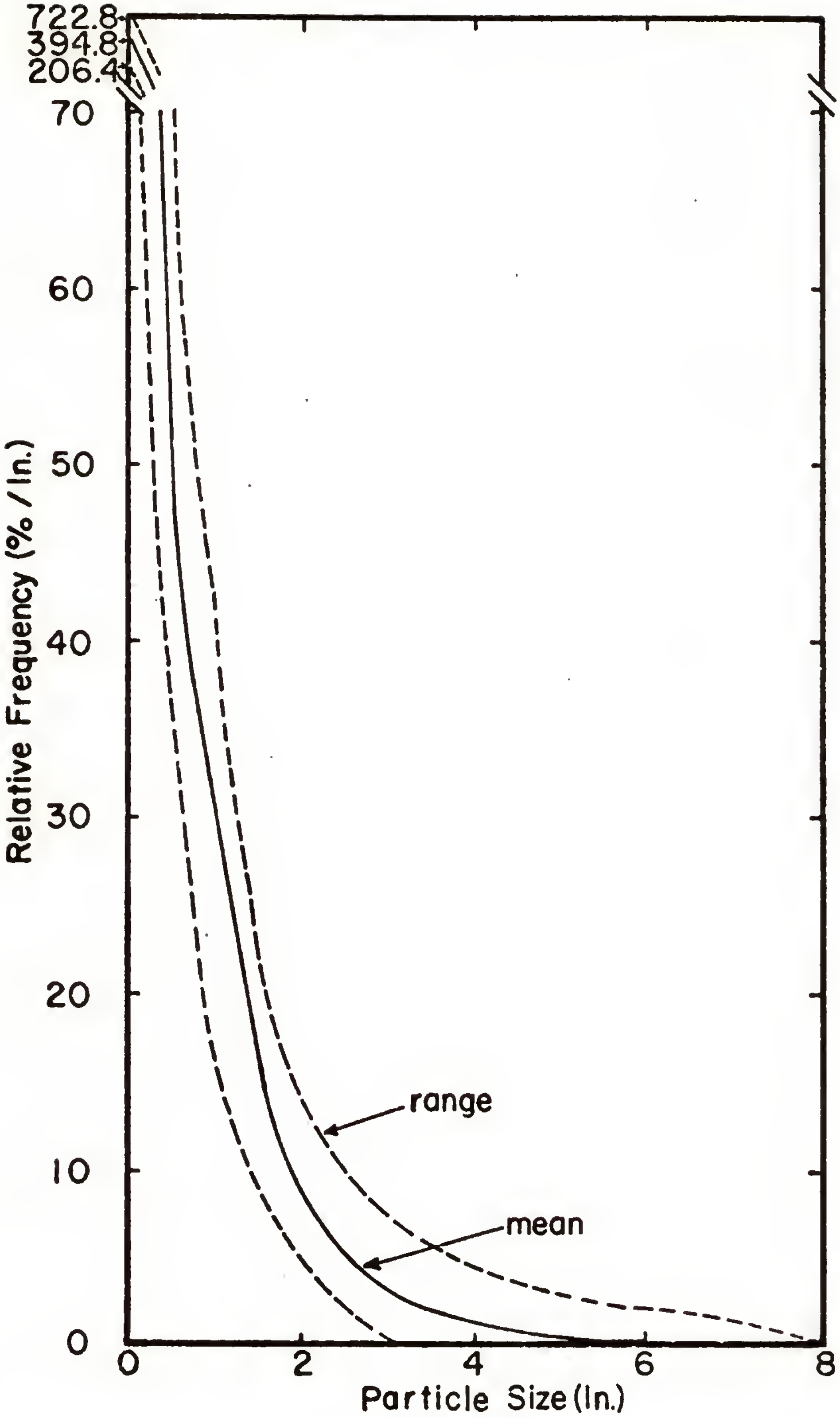


Figure 31. Particle size distribution of secondary shredded waste from Gainesville, Florida.

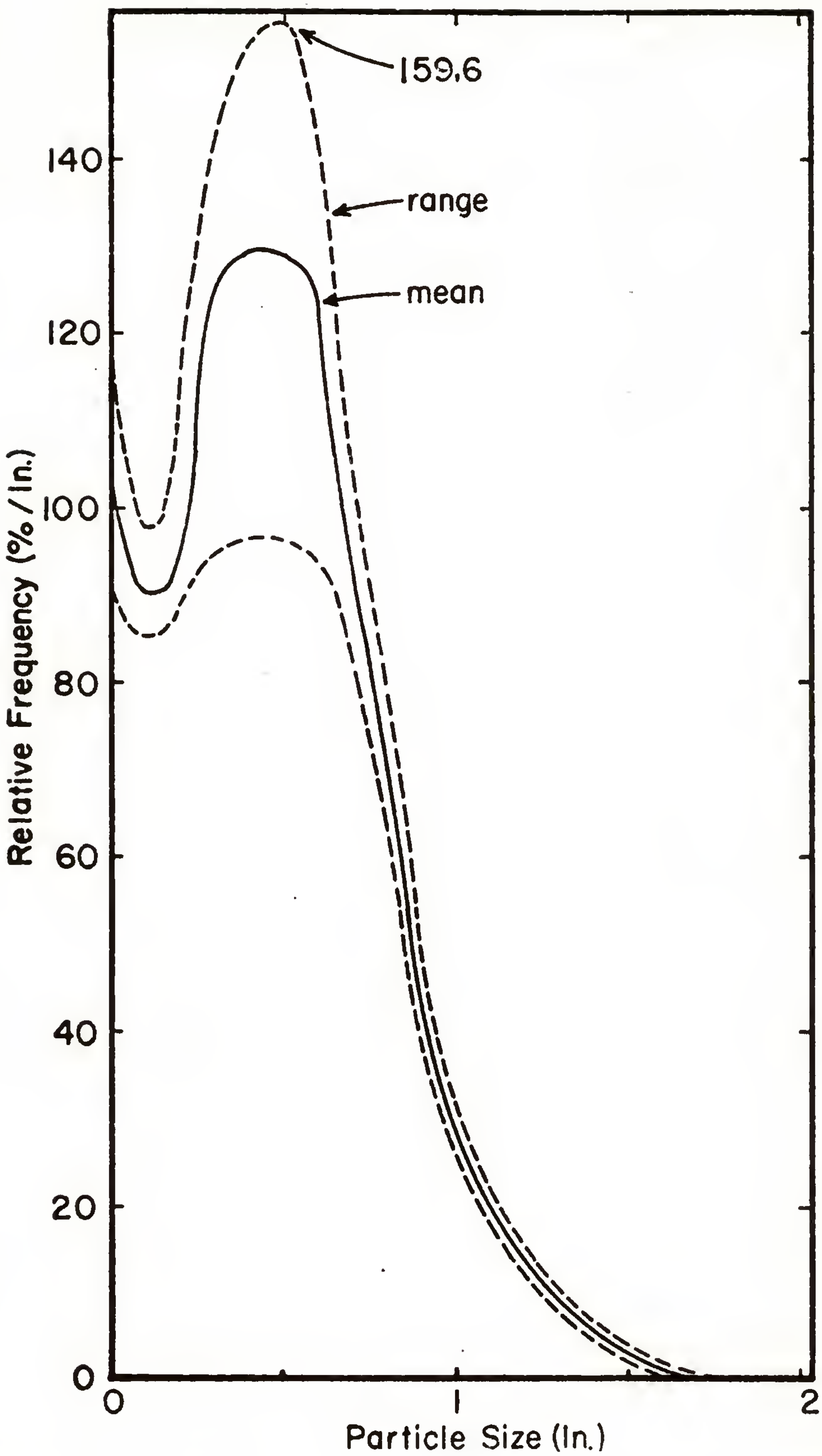


Figure 32. Particle size distribution of rasp shredded waste from Johnson City, Tennessee.

models (smooth curved common distributions) which were fitted to the data. The goodness-of-fit of the models to the data is indicated by the index of correlation, also provided in Appendix I. The techniques for determining both the mathematical models and the index of correlation will be described later in this chapter. Four distributions, arranged according to their constituents, are provided for each graph. This was done so the effect of the various shredders on each component could be readily compared.

The total relative frequency of all values less than the upper class boundary of a given class interval is called the relative cumulative frequency up to and including that class interval. A table presenting such relative cumulative frequencies is called a relative cumulative frequency table. A graph showing the relative cumulative frequency less than any upper class boundary plotted against the upper class boundary is called a relative cumulative frequency distribution, cumulative probability distributions, or more commonly, cumulative distributions. Cumulative distributions are often used for sieving data. A cumulative distribution for this example is shown in Figure 28. The median values can be obtained directly from these distributions by observing the appropriate reading for the 50 percent point. The median value for this example was 5.5 in.

Cumulative distributions for this and other wastes are provided in Figures 33-36. The distributions were obtained directly from the analytical data in a similar manner as

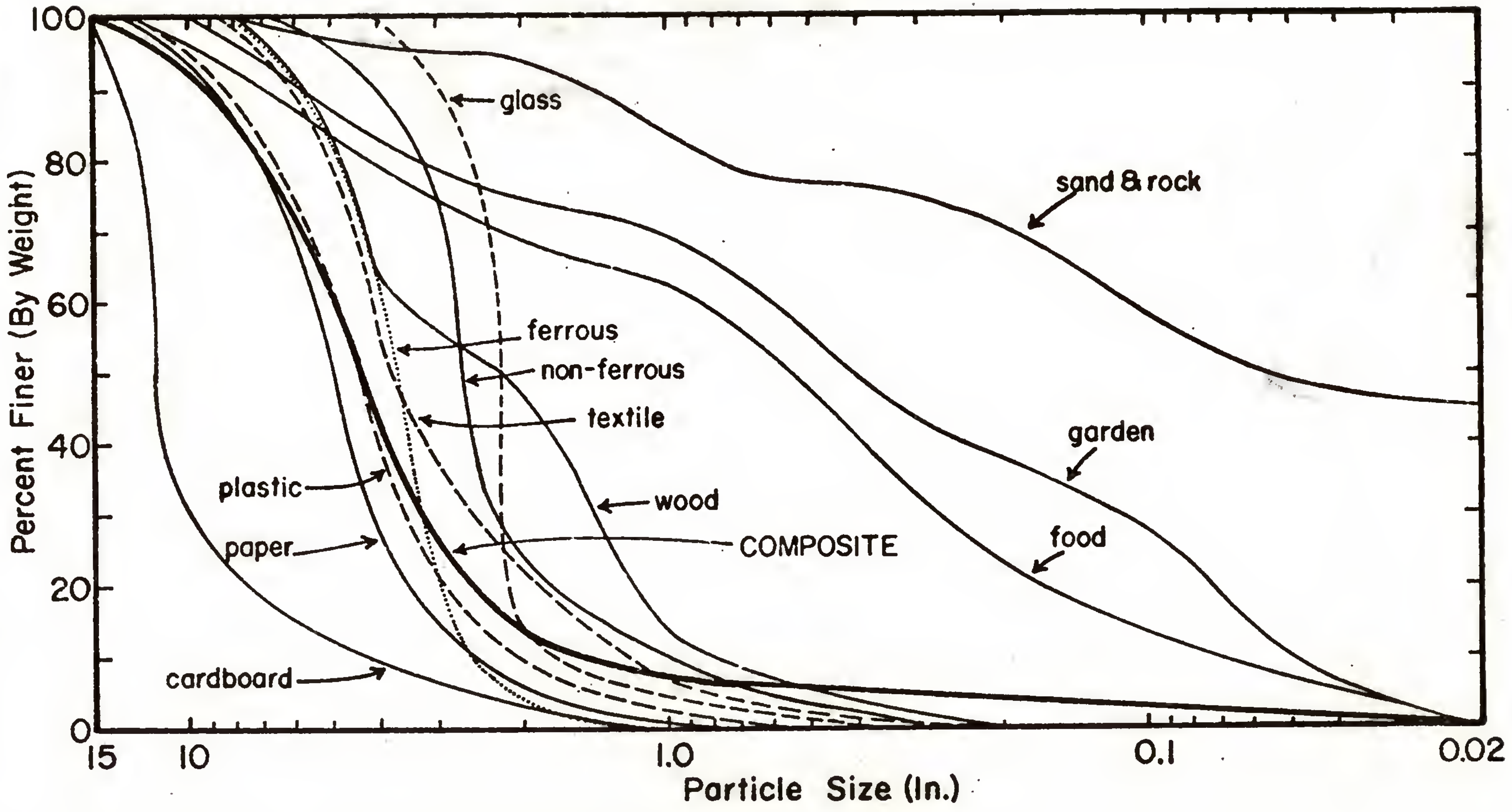


Figure 33. Cumulative distributions of raw waste.

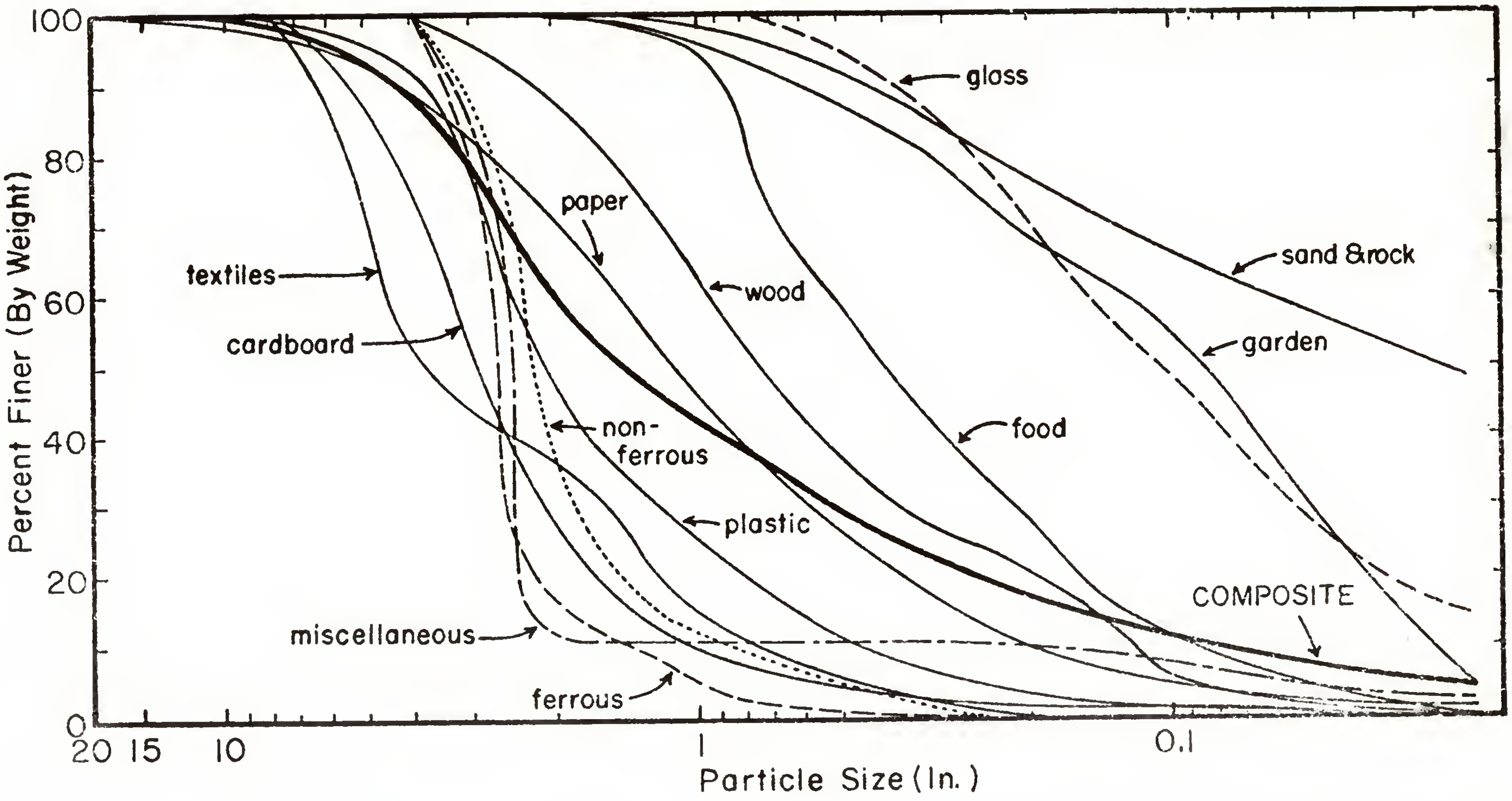


Figure 34. Cumulative distributions of primary waste.

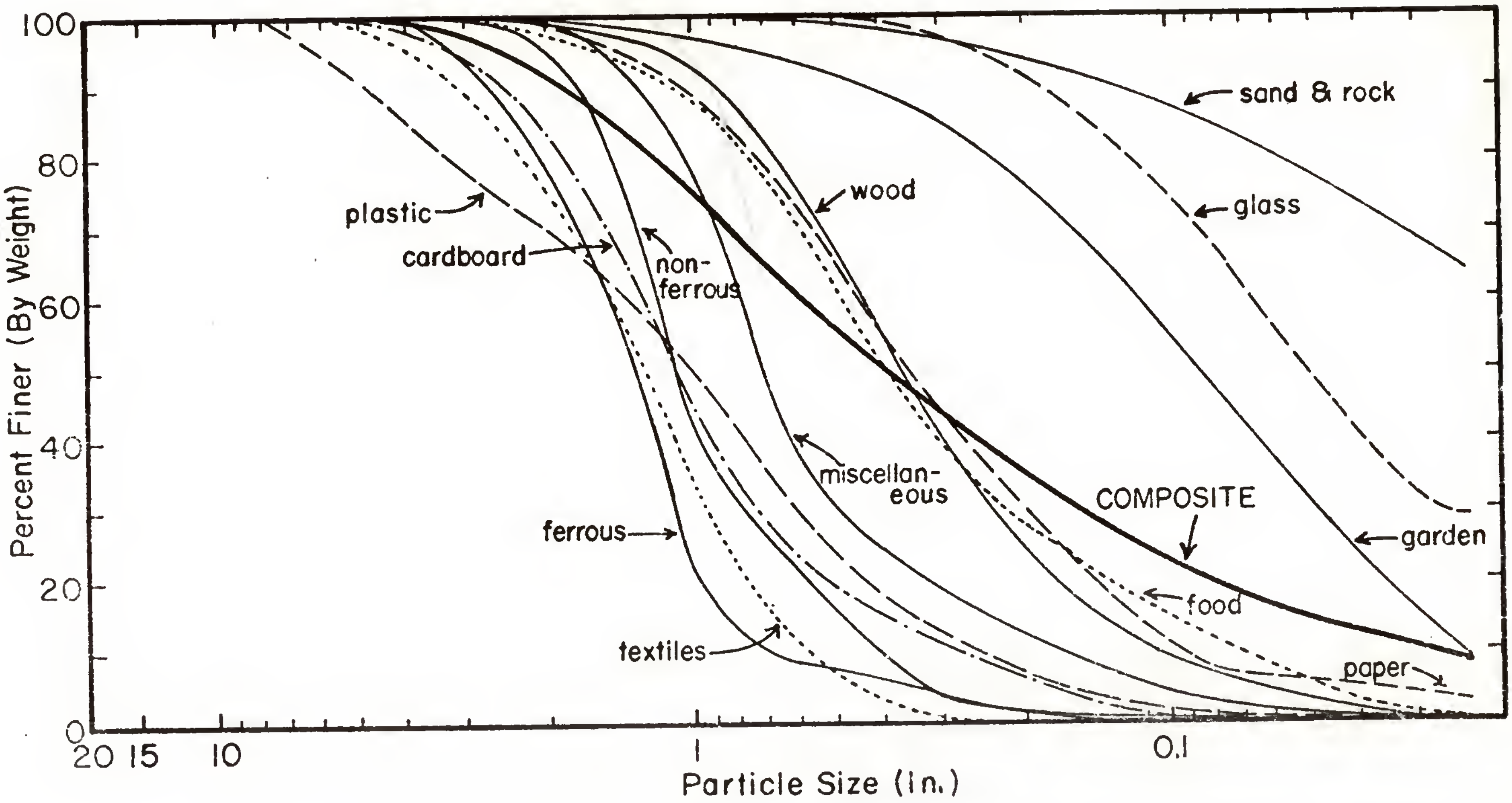


Figure 35. Cumulative distributions of secondary waste.

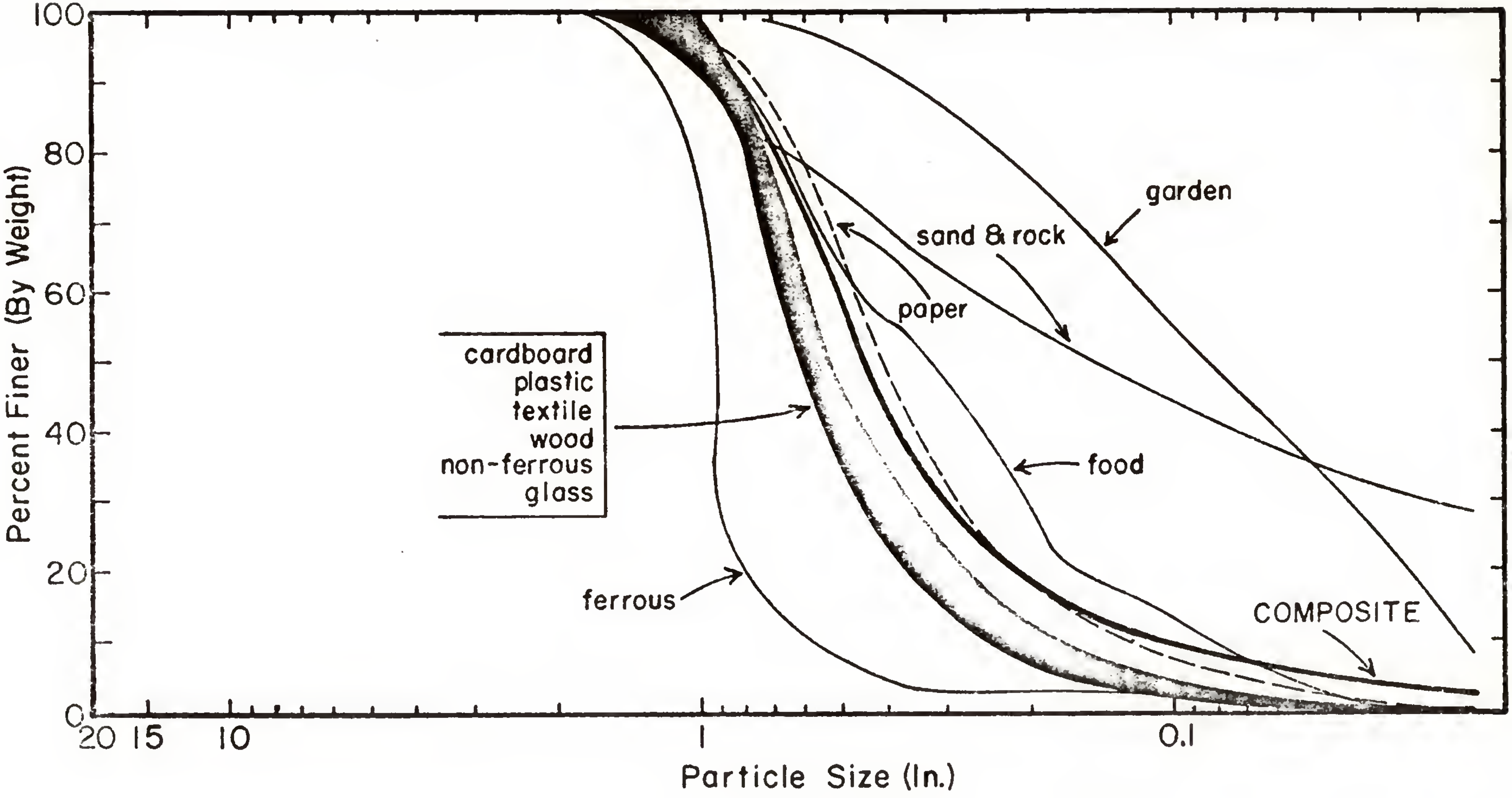


Figure 36. Cumulative distributions of rasp waste.

described in the above example. All the waste components of one refuse type are provided on one graph for comparitive purposes.

Sample Statistical Parameters

Various statistical parameters were calculated from the frequency distributions. The statistical parameters are found in Appendix H.

The theory of moments was used to calculate the arithmetic mean, $\bar{x}$, arithmetic standard deviation, s, skewness coefficient, S, and kurtosis coefficient, K [2,25,133-135]. They were calculated by the following equations:

$$\bar{x} = \sum_{\text{all } x_i} x_i \, p_X(x_i) \,, \tag{13}$$

$$s = \sqrt{\sum_{\text{all } x_i} x_i^2 \, p_X(x_i) - \bar{x}^2} \,, \tag{14}$$

$$S = \frac{h_3 - 3h_1h_2 + h_1^3}{s^3} \,, \tag{15}$$

and

$$K = \frac{h_4 - 4h_1h_3 + 6h_1^2h_2 - 3h_1^4}{s^4} \,, \tag{16}$$

where

$$h_1 = \sum_{\text{all } x_i} x_i \, p_X(x_i) \,, \tag{17}$$

$$h_2 = \sum_{\text{all } x_i} x_i^2 \, p_X(x_i) \,, \tag{18}$$

$$h_3 = \sum_{\text{all } x_i} x_i^3 \, p_X(x_i) \,, \tag{19}$$

$$h_4 = \sum_{\text{all } x_i} x_i^4 \, p_x(x_i) \ , \qquad (20)$$

and where

i = i^{th} class interval,

x_i = midpoint of i^{th} class interval (in.), and

$p_x(x_i)$ = probability of a particle falling into the i^{th} class and thus assuming the $x_i{}^{th}$ particle size (e.g., 6th column of Table 20 divided by 100).

A commonly used measurement of relative variability is the coefficient of variation, CV. It is defined as the standard deviation divided by the arithmetic mean,

$$CV = s/\bar{x} \ . \qquad (21)$$

It was used to calculate the variability of the sample data and was weighted as follows:

$$CV = \sum_{\text{all } x_i} w_i \, CV_i \ , \qquad (22)$$

where

w_i = width of i^{th} class, and

CV_i = coefficient of variation of i^{th} class.

Also, the theory of moments was used to calculate the geometric mean, $\bar{x}_g$, but instead of using x_i, the natural logarithm of x_i was used, i.e.,

$$\ln \bar{x}_g = \sum_{\text{all } x_i} (\ln x_i) p_x(x_i) \ . \qquad (23)$$

The values of $\bar{x}_g$ are reported in Appendix H.

The geometric standard deviation, $\ln s_g$, was calculated as follows:

$$\ln s_g = \sqrt{\sum_{\text{all } x_i} (\ln x_i - \ln \bar{x}_g)^2 \, p_x(x_i)} \ , \tag{24}$$

The values of $\ln s_g$ (which can be expressed as $s_{\ln \bar{x}_g}$) are reported in Appendix H.

The median value, $\tilde{x}$, was calculated by interpolation as follows:

$$\tilde{x} = L_m - \frac{w_m}{p_x(x_m)} \left(\sum_{i=1}^{m} p_x(x_i) - 50.0 \right) , \tag{25}$$

where

m = the class number in which median class interval is located,

L_m = upper class boundary of the median class (i.e., the class containing the median value),

w_m = class width of the median class interval, and

$p_x(x_m)$ = probability of a particle falling in the median class interval.

The median value can also be obtained directly from the cumulative distributions as indicated in Figure 28.

Model Fitting

It was imperative that a mathematical model be fit to the empirical data, so subsequent dealings with the variables would be simplified. A tractable, smooth, common probability distribution was desirable to summarize the available data.

The model selection techniques described in Benjamin and Cornell's Probability, Statistics, and Decision for Civil Engineers [134] were utilized. In summary, this technique consisted of plotting the data and then choosing general types of probability distributions which appeared to represent the data. The statistical parameters of the samples (Appendix H) were used to estimate model parameters. The values of the parameters were determined and the models plotted with the empirical data. The model which most closely represented the data was initially chosen. The final choice was that the index of correlation for each model must exceed 0.70 for every distribution except the miscellaneous category. Indices of correlations greater than 0.90 were preferred.

Occasionally the empirical data were found to be not reasonably represented by common probability models. This was predominantly due to bimodality of the distributions. Thus, a sum of two theoretical distributions was used to adequately define these complex distributions. Each theoretical distribution was weighted so the sum of the areas under both of the distributions equaled 100 percent.

The equations of the chosen models are provided in Appendix I. Also provided is a table of common probability distributions (Table I-1). This is a listing of the different types of probability distributions which were used for the empirical data. The table provides the equations for the distributions, once the parameters have been defined. For convenience, the chosen models have been symbolized, e.g., EX (6.30). The notation, EX (6.30), represents an exponential probability distribution in which λ has a value of 6.30. The equation is:

$$y = 6.30 \exp(-6.30x) \quad . \tag{26}$$

The notations and the equations for the other distributions also are provided in the table.

The notation, $\Gamma(x)$, which is used in the gamma and beta distributions represents the gamma function; values can be readily obtained from standard mathematical tables.

Table I-1 also gives the means, variances and ranges of the random variables for the theoretical models. As noted previously, a single parameter was sufficient to provide a complete characterization of some distributions, e.g., exponential. Two parameters were required by others; the most parameters required were four by the beta distribution. It is important to limit the range of the beta distribution as its value explodes when increased beyond its limits.

The goodness-of-fit of the models to the empirical data was calculated next. This was done by calculating the index of correlation coefficient (or non-linear correlation coefficient). The index, ρ, is a measure of the scatter of data from the theoretical curves, and was calculated by the equation:

$$\rho = \sqrt{1 - (s_y^2)/\sigma_y^2} \tag{27}$$

where

$$s_y^2 = \sum_{\text{all } i} w_i (Y_{act._i} - Y_{est._i})^2 , \tag{28}$$

$$\sigma_y^2 = \sum_{\text{all } i} w_i (Y_{act._i} - \bar{Y})^2 , \tag{29}$$

and w_i = width of i^{th} class,

$Y_{act._i}$ = actual values of the dependent variable Y (%/in.) obtained from the empirical data (last column of Table 20),

$Y_{est._i}$ = estimated values of Y (%/in.) obtained from the theoretical equation, and

$\bar{Y} = 100/\Sigma w_i$ = mean value of Y (%/in.).

The symbol s_y is called the standard error of estimate and is a measure of variation or scatter of data about the line of regression. The total variance of Y is defined as σ_y^2 and is the sum of squares of the deviations of the values of Y from the mean $\bar{Y}$. Both s_y^2 and σ_y^2 were weighted by multiplying each variance by its respective class interval width (w_i).

The index of correlation varies from 0 to 1.0. A zero value is obtained when there is no correlation between the data and the assumed equation (or distribution). A high value of σ indicates a high correlation. A value of 1.0 means that each data point falls on the fitted distribution.

The values of the index of correlation are provided in Table I-2 of Appendix I. They ranged from 0.65 to 1.00 and averaged 0.94. Low readings were obtained for components with low percentage composition, while high values were obtained for the major components.

Analysis of Variance

In order to determine the accuracy of an analytical procedure it is necessary to analyze some "true" or "standard" samples, and then compare the analytical results with these known values. Unfortunately, since there were no standard refuse samples in which the size of the particles were known, it was impossible to determine the accuracy of the sieve analytical methods. Thus, the effort concentrated on reproducibility.

Variation is characteristic of all experiments. Experimental error is a measure of the variation which exists among observations on experimental units treated alike. Variation comes from two main sources. First, there is the inherent variability which exists in the different materials. Secondly, there are variations in the results from lack of uniformity in the analytical procedures. The latter variation determines the reproducibility or precision of an experiment.[1]

In most analytical procedures, it is difficult to partition the total experimental error into experimental error caused by variations in samples and the experimental error caused by non-uniformity in analytical procedures. In many cases, the analytical procedures would destroy or damage these samples since replications cannot be made on the same sample.

---

[1] The considerable variation of the waste samples is shown by Figures 29-32 and Appendix H. The range is used to indicate the variation in the figures while the weighted coefficient of variation is used in the Appendix.

The typical procedure to determine the experimental error of an experiment is to analyze replicated samples and then determine the variation of the measurements. Either the coefficient of variation or the standard error of means, $\sigma_{\overline{X}}$, is then calculated and used to estimate the experimental error. The standard error of means, $\sigma_{\overline{X}}$, is defined as

$$\sigma_{\overline{X}} = \frac{s}{\sqrt{n}} , \tag{30}$$

where s = standard deviation of means, and

n = number of replications.

The experimental errors of the sieving and classification procedures were determined by selecting different raw, primary and secondary samples (R-10, P-11, and S-12, respectively) and analyzing each sample 5 times. Then, the sieve fractions of each sample were gently mixed together prior to the next analysis.

Repeated analysis of the same sample eliminated the experimental error due to the material. The only variation was due to the analytical procedures plus an error introduced in damaging the particles by the repeated analysis. This error was expected to be small compared to errors introduced by different samples.

The reproducibility results are found in Table 21. The mean particle sizes are provided for different sieve runs for each sample. The analysis definitely showed sieving resulted in a reduction of particle size with repeated analysis, thus introducing a new source of variance. The particle size of

Table 21

Reproducibility of Sieving Refuse
with the Gilson Sieve

Sieve Run	Mean Particle Size (in.)		
	Raw (R-10)	Primary (P-11)	Secondary (S-12)
1	6.2237	1.7167	0.8341
2	5.2686	1.6975	0.8277
3	5.0886	1.6505	0.8103
4	5.0372	1.6695	0.8122
5	5.2254	1.6534	0.8182
$\overline{x}$	5.3687	1.6775	0.8205
s	0.4873	0.02877	0.01019
$s_{\overline{x}}$	0.2179	0.012866	0.00456
CV	9.07%	1.71%	1.24%
Sample size (gms.)	6664.7	945.7	1435.2

all samples was reduced by the repeated analysis. Although a new variance was introduced, the total variance was small. The standard errors of means for the primary and secondary waste were 0.0129 and 0.0046 in. The standard error of the raw refuse was considerably greater at 0.218 in. The greatest part of this variation was caused by a considerable reduction in particle size of the raw refuse by the first sieve run. For example, the mean particle size was altered from 6.22 to 5.27 in. A standard error of mean and coefficient of variation of 0.0549 in. and 2.13%, respectively, would be obtained if this first run for raw waste were discounted. The data also show that increased reproducibility was obtained with the finer particle waste.

The results also are shown in the cumulative frequency distributions provided in Figure 37. Only the range of the distributions for the primary and secondary wastes are provided (as a result of the closeness of the curves). Reasonably tractable results were obtained for all waste, thus proving the sieve method is reproducible. Narrower bands could have been obtained if the digression of particle size, due to repeated analysis, could have been partitioned.

A large variation was found in the larger particles (greater than 4 in.) of raw refuse. The data definitely indicate repeated analysis was responsible for most of the variation. If the first analysis was discounted, a much narrower band would be obtained, thus reducing the variation considerably. A review of the components of raw waste showed a drastic reduction of the particle size (due to the first run) of garden, cardboard and paper components. These more fragile components add proof that the variation between the first and second run was due to damaged particles.

The reproducibility of the classification technique was obtained in a similar fashion as the above sieve analysis runs, but the estimated composition of the samples was used instead of the mean particle size. Table 22 gives the results of this analysis for five of the refuse components. These components were chosen because they made up the bulk of the refuse. In addition, it was expected that a larger error

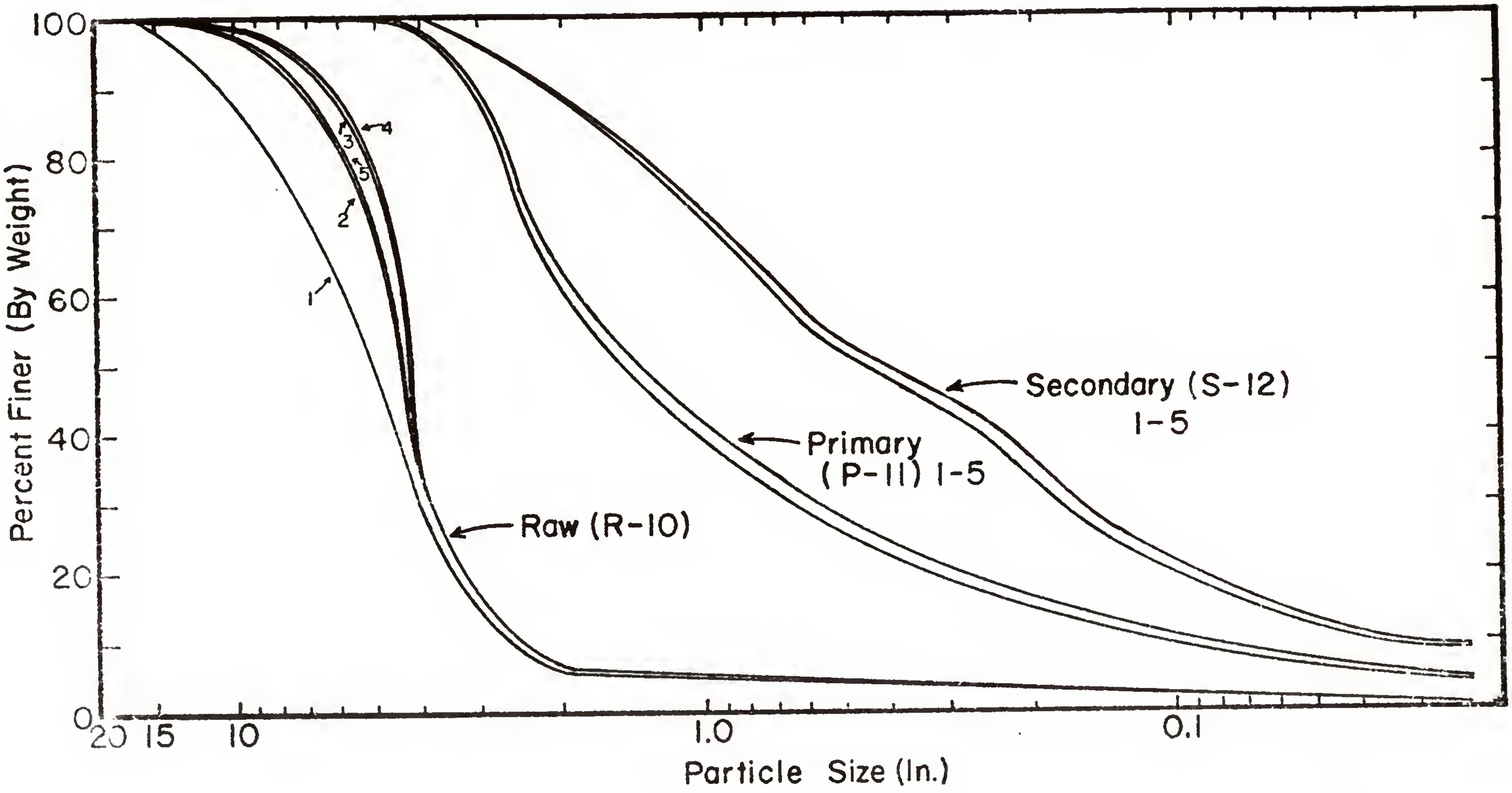


Figure 37. Reproducibility of sieving.

would be exhibited by them since a greater number of subjective decisions were made in their classification, e.g., shattered glass versus sand, paper versus cardboard, wood versus garden.

Table 22

Reproducibility of Classification of Refuse

Statistic (%)	Waste Component				
	Garden	Cardboard	Paper	Ferrous	Glass
A. Raw waste (Sample No. R-10)					
$\bar{x}$	0.46	4.06	61.76	11.66	9.91
s	0.0493	0.0340	0.1947	0.1128	0.0566
$s_{\bar{x}}$	0.000486	0.01521	0.08706	0.05044	0.0253
CV	10.75	0.84	0.32	0.97	0.58
B. Primary waste (Sample No. P-11)					
$\bar{x}$	0.46	18.40	41.00	11.17	9.25
s	0.2394	2.7896	2.2839	0.1214	0.8673
$s_{\bar{x}}$	0.1071	1.2475	1.0214	0.0543	0.3879
CV	52.00	2.79	2.28	0.12	0.87
C. Secondary waste (Sample No. S-12)					
$\bar{x}$	0.99	27.58	30.21	13.64	15.16
s	0.2167	1.6424	2.7051	0.0942	1.578
$s_{\bar{x}}$	0.0969	0.7345	1.9897	0.0421	0.7057
CV	21.78	5.95	8.96	0.69	10.41

In general, the classification technique also was relatively reproducible. Low experimental errors were obtained. Several trends appeared. First, the coefficient of variation was found to be greater for waste with finer particles.

Obviously, it is more difficult to differentiate smaller particles. Secondly, high coefficients of variation were obtained for garden waste because of its low percentage and the difficulty in differentiating it from wood waste.

Another experiment was provided to determine the variation of refuse test samples from the same gross sample. This information was desirable since "twin test samples" from the same bag were utilized in the compression cylinder test. Basically, this experiment consisted of selecting 4 gross samples from the primary waste (P-5, P-6, P-9, P-10) and 4 from secondary (S-6, S-7, S-8, S-15). Each gross sample was gently mixed and two test samples randomly selected, resulting in 8 pairs of test samples. The samples were analyzed as previously discussed.

The analysis of variance (randomized complete-block design with equal subsamples) was utilized in order to determine the experimental error. This is essentially an arithmetic process for partitioning the total sum of squares (variations) into components associated with recognized sources of variation. The mean particle size analytical data are provided in Table 23. The analysis of the variance is found in Table 24.

The analysis of variance table shows a very significant difference between the refuse types (primary versus secondary). No significant difference was found between the twin samples (even of 90 percent confidence level). Thus it was concluded that the variation between twin samples (from the same gross

Table 23

Analysis of Variance Data of Twin Refuse Samples

Refuse Types	Twin Samples	Mean Particle Size (in.)		Twin Sample Totals (in.)	Refuse Type Total (in.)
Primary	P-5	2.8123	3.1962	2.0085	19.6307
	P-6	2.0649	4.2794	6.3443	
	P-9	1.9253	1.9429	3.8682	
	P-10	1.2859	2.1238	3.4097	
Secondary	S-6	0.5242	0.9039	1.4281	4.9768
	S-7	0.8960	0.7275	1.6235	
	S-8	0.4782	0.4211	0.8993	
	S-15	0.5712	0.4547	1.0259	
Total		24.6075		24.6075	24.6075

Table 24

Analysis of Variance for Twin Refuse Sample Data

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Among refuse types	1	13.4210	13.4210	23.19
Between twin samples within refuse types	6	3.4722	0.5787	1.56
Within twin samples	8	2.9719	0.3714	
Total	15	19.8649		

sample) was not significantly different from the variation between test samples from different gross samples as far as the mean particle size is concerned.

The standard error of means, $s_{\bar{x}}$, was calculated for the difference between the same twin samples, as follows:

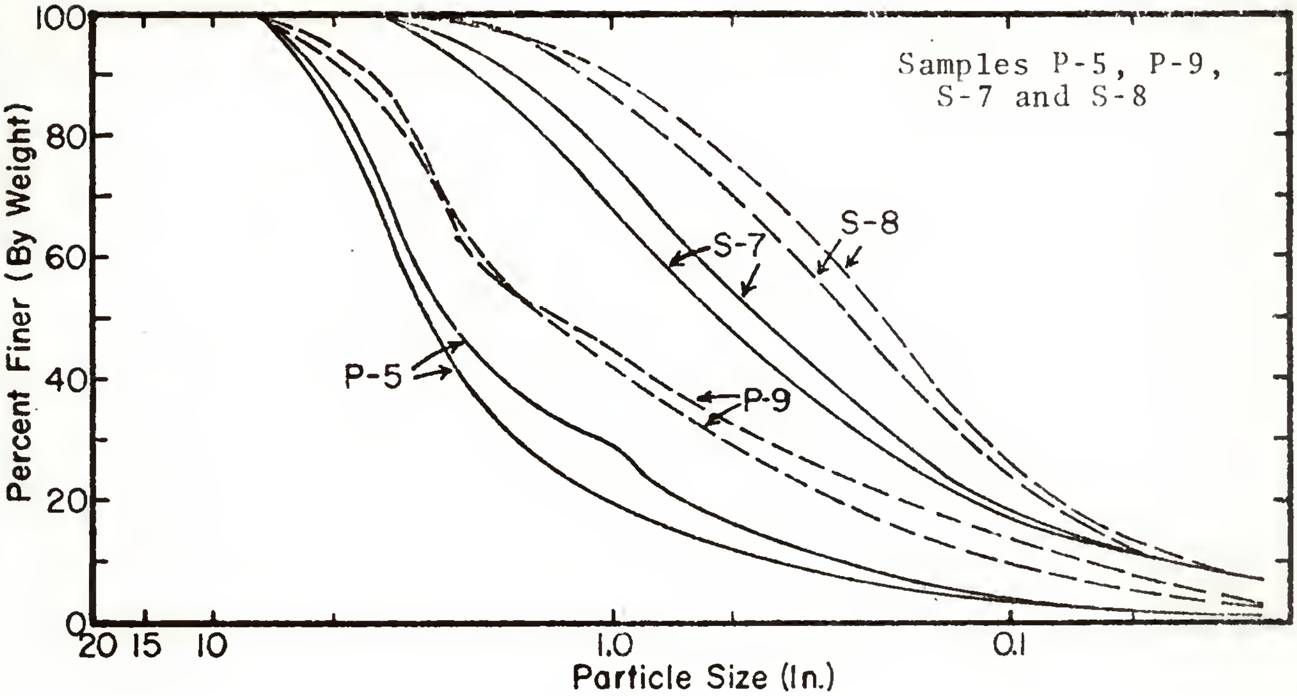
$$s_{\bar{x}} = \sqrt{\frac{MS_e}{n}} = \sqrt{\frac{0.3714}{8}} = 0.2155 \text{ in.} \qquad (31)$$

Since no significant difference was found between the twin refuse samples, the two errors may be pooled to form a new standard error, as follows:

$$s_{\bar{x}} = \sqrt{\frac{3.4722+2.9719}{14\ (14)}} = 0.1813 \text{ in.}$$

This value is considerable greater than the results obtained by sieving the same samples repeatedly (Table 21), as standard errors of 0.01287 and 0.00456 were obtained for the primary and secondary waste, respectively. Obviously, the experimental error of the twin refuse samples is many times greater than the experimental error of the analytical procedure.

The wide difference between twin samples is reflected by the cumulative distributions shown in Figure 38. The distributions tended to diverge at the larger sizes and overlap at the smaller sizes. The greatest variation was found for twin samples P-6, P-10 and S-6. A large piece of paper, found in the 8-to 16-in. fraction of one twin sample of P-6, drastically altered its size distribution compared to the



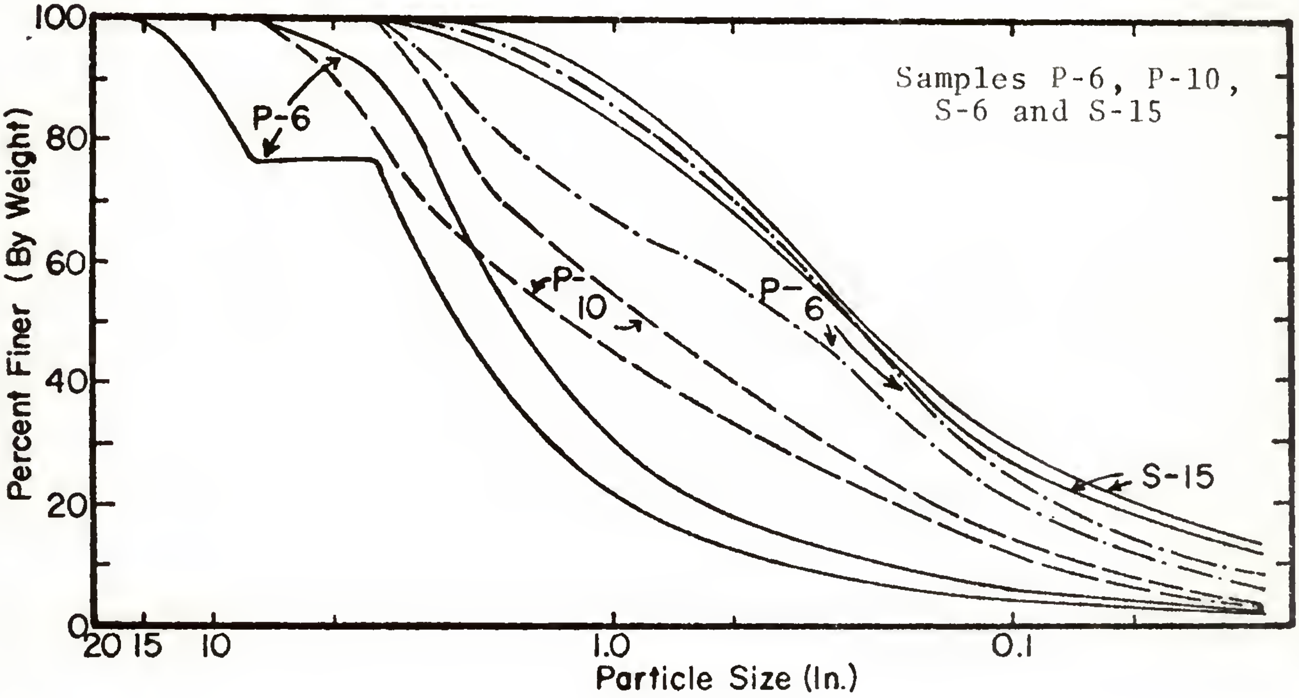


Figure 38. Variation of particle size of twin samples.

other twin sample. The variations of all of these distributions were considerably greater than those found in Figure 37.

The particle size variation between the various refuse samples of each refuse type was determined utilizing the mean particle size. The twin samples were averaged and used as independent samples. The variation for all of the samples are shown in Tables 25 and 26.

The analysis of variance was used to determine the experimental error utilizing the randomized complete-block design with unequal replications. The analysis of variance table shows a highly significant difference between the refuse types.

The standard error of mean, $s_{\bar{x}}$, for all of the samples was 0.0912. This is considerably less than the $s_{\bar{x}}$ value of 0.1813 obtained for the twin samples. Obviously, the greater number of samples (and thus a larger degree of freedom) contributed to the lessening of the value. Raw waste contributed the greatest to the standard error (0.3027 in.) while the rasp contributed only 0.0054 in. The rasp samples were very uniform.

In summary, the sieve analysis standard errors of means for raw, primary and secondary waste were found to be 0.0549, 0.0129 and 0.0046 in., respectively. The values were determined by analyzing the primary and secondary samples five times, while raw waste was analyzed only four times (the first run was discounted due to a considerable reduction in particle size by the analysis). Rasp waste was found to have

Table 25

Analysis of Variance Data of Refuse Sieve Samples

Waste Type	Number Samples	Mean (in.)	Sum of Squares (in.^{2})	Standard Error of Means (in.)	Coefficient of Variation (%)
Raw	10	5.2918	8.2448	0.3027	18.09
Primary	14	2.0004	3.9229	0.1468	27.46
Secondary	15	0.7432	0.4951	0.0486	25.30
Rasp	4	0.4720	0.0004	0.0054	2.30
Total	43	(2.1851)	12.6632	(0.0912)	(26.08)

Table 26

Analysis of Variance of Refuse Sieve Sample Data

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
Among refuse types	3	139.9186	46.6395	143.64
Within refuse types	39	12.6632	0.3247	
Total	42	152.5818		

the least variation. The classification standard error of means varied from 0.0005 to 1.99 percent, depending on the type of component and waste type.

CHAPTER VI

EXPERIMENTAL RESULTS - DENSITY AND COMPRESSIBILITY

Introduction

Some 79 test samples were analyzed by the combined density-compression test (Appendix A). Most of the compression samples were "twin samples" to the particle size test samples as both types were obtained from the same gross samples. In addition, many of the compression test samples were replicated (depending on the size of the gross samples), forming some 31 pairs of twin compression samples. Several of the density-compression samples were also reconstructed from the sieve analysis samples (including all of the raw waste samples).

It was necessary to modify most of the raw waste test samples prior to their use in the density-compression test cylinder, since most of the larger raw waste particles (8 to 16 in. size) were too large for the test cylinder. In addition, only one or two large particles existed in many of the gross samples; hence, it was obvious that representative test samples could not be obtained without modification. Thus, in order to overcome this problem, the large particles were removed from samples R-1 through R-7. The large particles were cut in half for samples R-8 and R-9 (to form 4- to 8-in. particles); sample R-10 was not modified. The composition and screen analysis data were modified accordingly when used with the density-compression data.

The revised raw waste particle size distribution is shown in Figure 39. The mean particle size of this distribution is somewhat smaller than its parent distribution (Figure 29). The mean particle size of the modified raw waste test samples varied from 3.52 to 6.22 in., with a mean of 4.32 in. The standard deviation of the distribution averaged 1.86 in.

Analytical Techniques

Techniques used in the combined density and compression analyses were straightforward and did not present significant problems. Some 47 different pressures (from 0 to 174.7 psi) were applied, incrementally in a uniform manner, to each sample and then the location of the top of the piston was measured. The volume of compressed material was determined from this reading. It usually took about 10 seconds to measure the location of the piston after reaching each respective pressure. The total time of the test (from the time when the pressure was first applied until the time when the last pressure was released) averaged 29.3 minutes. Another 30 minutes were required for test preparation and for cleaning up. The average sample size was 3.228 lbs.

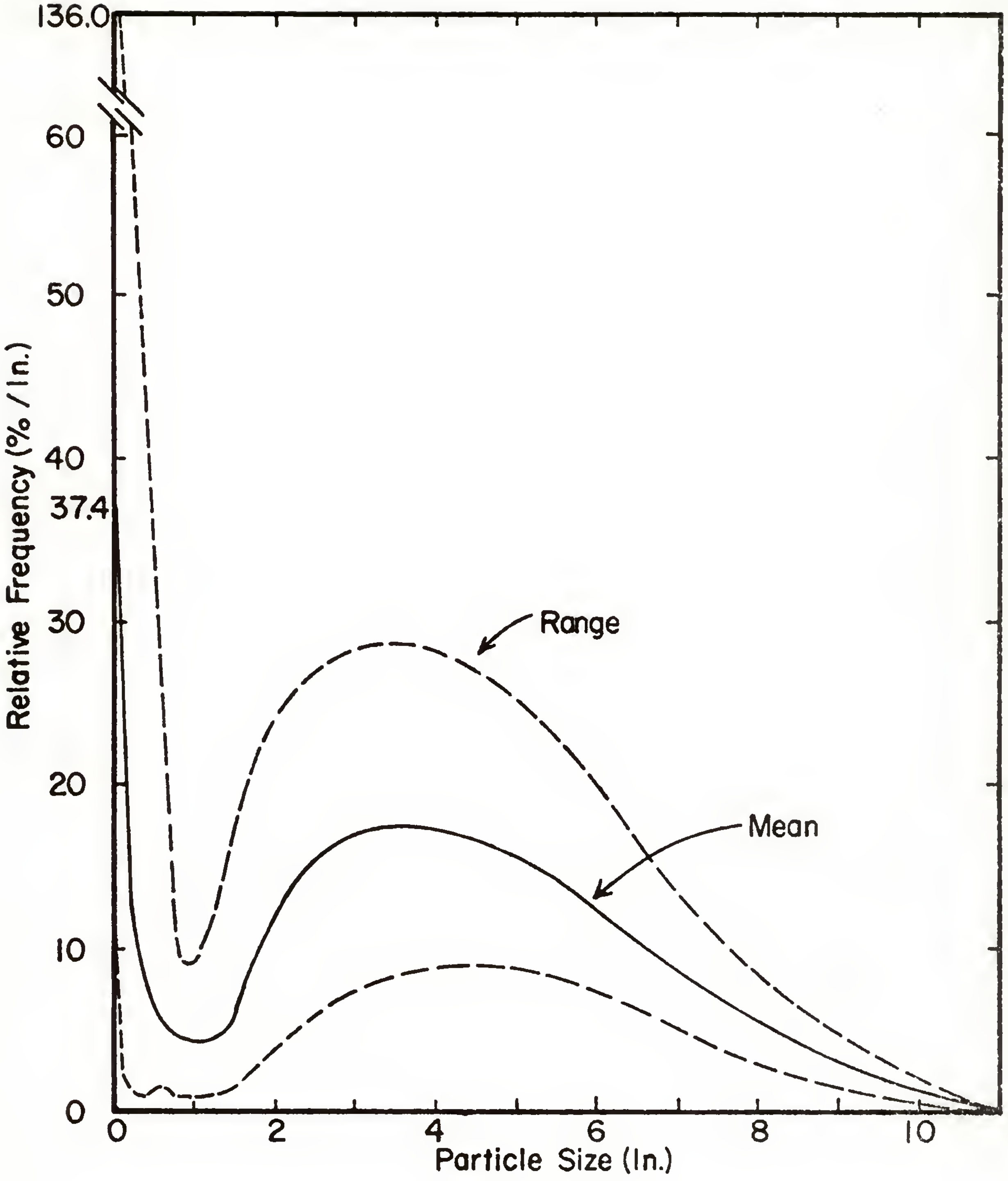


Figure 39. Particle size distribution of modified raw waste from Gainesville, Florida.

Not all of the 47 pressure readings were obtained for each sample because the filler plates initially were not available. Thus, when very compressible materials were encountered, the ram of the hydraulic press reached its limit of extension without reaching the full range of pressure readings. This was overcome by placing the plates underneath the samples in order to raise them.

The testing procedures usually required two persons to move the heavy piston and cylinder. Also, the hand-pumping of the hydraulic cylinder was physically demanding.

Occasionally, a mild boom (or popping sound) occurred in the material during the testing of raw waste. This resulted from bottles and cans collapsing. The cans collapsed from 10 to 30 psi (averaging 19.2 psi) and the bottles collapsed at 5 to 35 psi (averaging 16.6 psi). The volume of the samples was reduced drastically after these containers caved in.

Display of Results

The density and compression data were recorded on 79 "Density and Compression Test Data Forms," a copy of which is provided in Appendix G. The data forms had 53 different depth gage readings; 6 were duplications to determine the rebound characteristics of the waste. In addition, 6 interpolations were required, resulting in a total of 59 different values. Only 21 of these values were utilized in the presentation of the data.

It was necessary to average the results of the replicated samples since they were not independent samples. Then, these samples were used to estimate each respective population, e.g., the 10 averaged raw waste samples were used to estimate the raw waste population. This was done for each pressure value of each waste population. The independent results were then averaged and the standard error of means calculated.

The graphical display of the data, for each waste type, is shown in Figures 40 to 43. The 95 percent confidence limits have been provided around the curves, giving an indication of the variability of the data. The three rebound curves also are indicated.

Analysis of Variance

It was impossible to determine the accuracy of the combined density-compression test since there were no standard refuse samples in which either the bulk density or the compressibility were known. Thus, only the variation of the samples and the reproducibility of the testing procedures could be determined.

The variations of different gross samples, previously shown by Figures 40 to 43, also are indicated in Table 27 at pressure levels of 0, 10 and 100 psi. The variations are provided for different waste types and are indicated by the standard errors of means, $s_{\bar{x}}$, and the coefficientsof

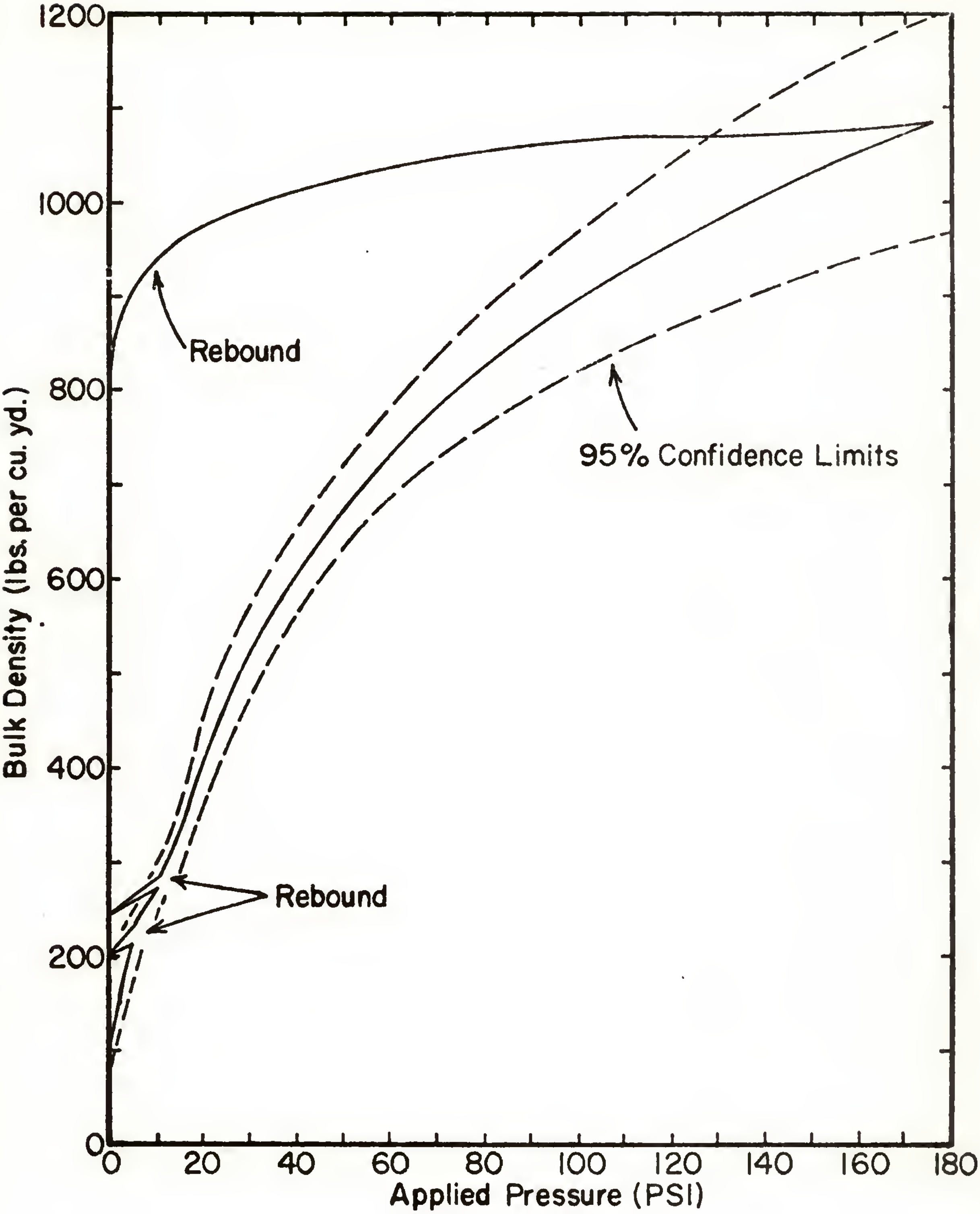


Figure 40. Compressibility of modified raw solid waste.

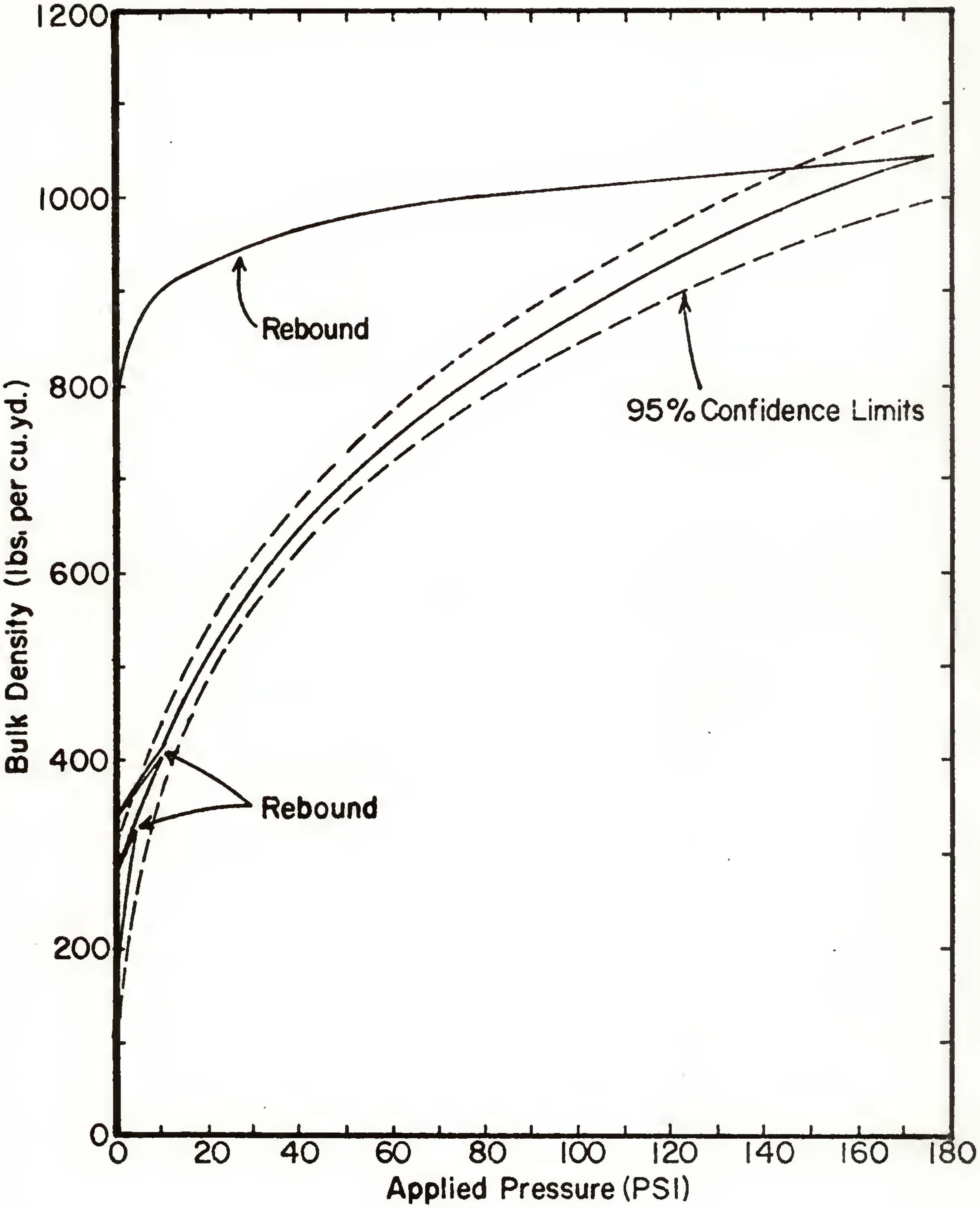


Figure 41. Compressibility of solid waste after primary shredding.

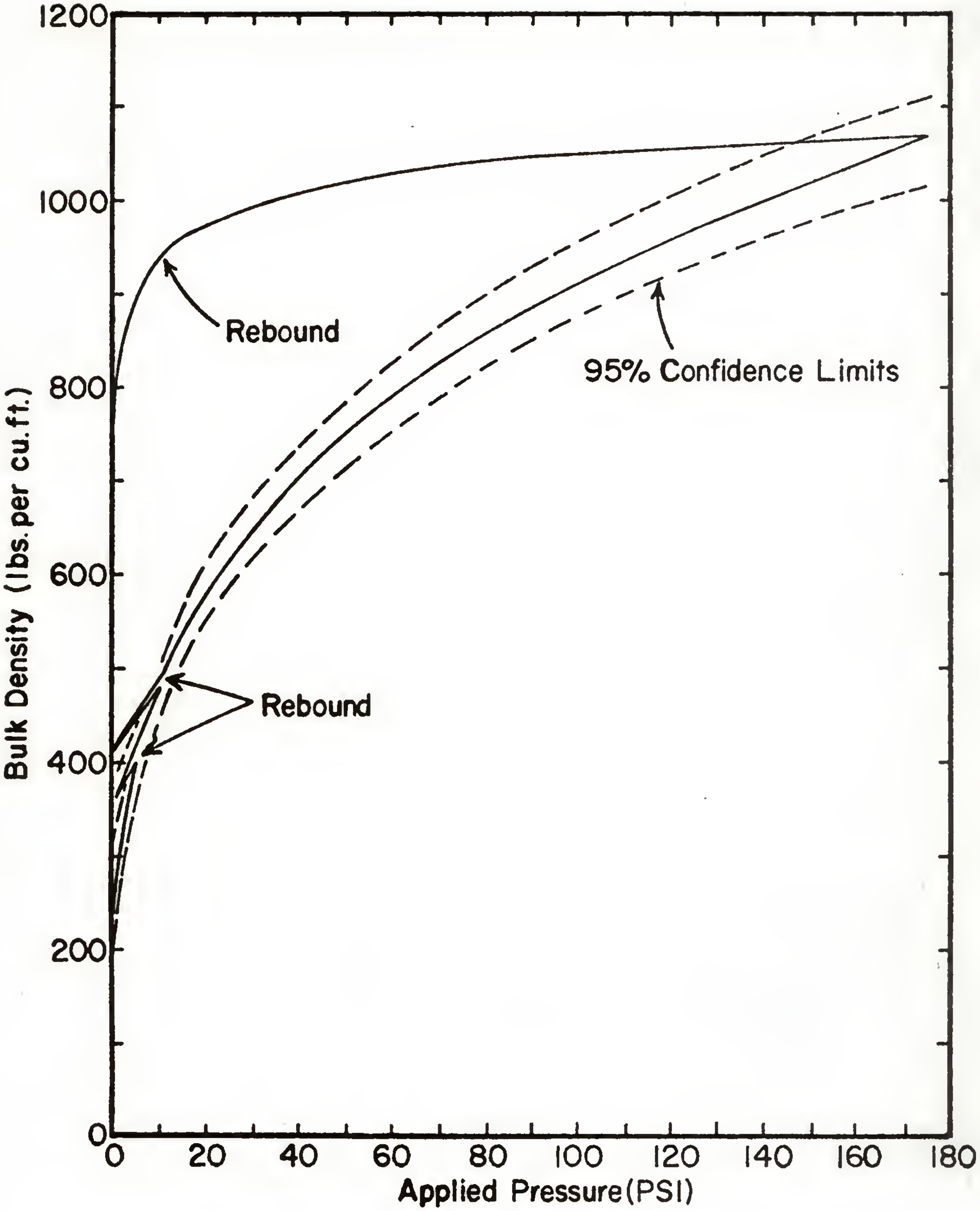


Figure 42. Compressibility of solid waste after secondary shredding.

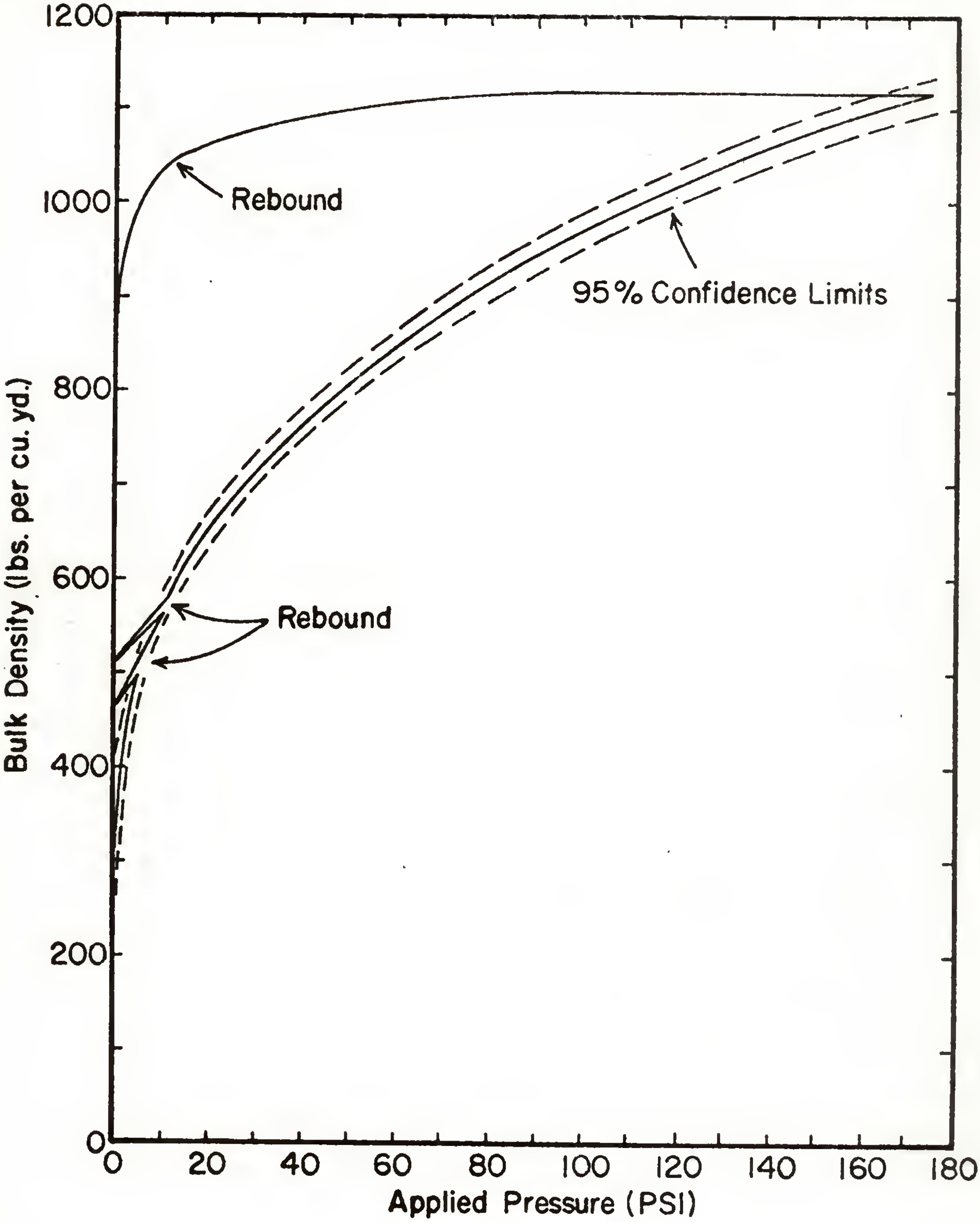


Figure 43. Compressibility of solid waste passed through a rasp.

Table 27

Analysis of Variance of the Density-Compression Data for Different Waste Types

Type of Variation	Waste Types	Pressures (psi) 0 n	0 $\bar{x}$ (ppcyd)	0 $s_{\bar{x}}$ (ppcyd)	0 CV (%)	10 n	10 $\bar{x}$ (ppcyd)	10 $s_{\bar{x}}$ (ppcyd)	10 CV (%)	100 n	100 $\bar{x}$ (ppcyd)	100 $s_{\bar{x}}$ (ppcyd)	100 CV (%)
Different Gross Samples	Raw	10	98.7	11.32	36.44	10	270.2	13.30	15.56	10	899.7	37.25	13.09
	Primary	14	84.1	7.41	32.97	14	398.7	14.32	13.44	12	879.4	18.73	7.38
	Secondary	15	136.5	8.52	24.20	15	475.6	11.18	9.11	15	916.4	20.77	8.78
	Rasp	4	256.6	6.68	5.21	4	558.0	7.06	2.53	4	975.4	9.55	1.96
Twin Samples	Raw	20	98.7	11.52	36.90	20	268.6	11.87	19.76	20	895.5	28.14	14.05
	Primary	18	88.5	6.14	29.45	18	382.3	13.37	14.84	14	874.6	18.60	7.96
	Secondary	16	137.7	8.10	23.54	16	474.9	15.45	13.01	16	930.1	23.81	10.24
	Rasp	8	252.1	5.14	5.77	8	548.6	8.36	4.31	8	960.8	15.43	4.54
Same Gross Sample (R-10&S-6)	Raw	4	110.1	7.46	13.56	4	304.7	35.62	23.38	4	873.3	60.85	13.93
	Secondary	4	117.5	2.15	3.67	4	410.7	6.59	3.21	4	837.7	25.89	6.18
Same Test Sample (P-10&S-7)	Primary	5	66.7	1.09	3.66								
	Secondary	5	92.5	0.72	1.74								

NOTE: ppcyd = lbs. per cu. yd.

variation, CV. The number of samples, n, and the mean values, $\overline{x}$, are also provided in this table.

The experimental error of the density test was obtained directly by repeated analysis of the same test sample, thus eliminating the experimental error due to variations of different samples. This procedure could not be duplicated by the compression test because it would destroy or damage the particles. The gentle placement of particles into the test cylinder (and the later gentle mixing of samples) should not have any significant effect in altering the particles for the density test.

Two test samples (P-10 and S-7) were each analyzed five times with the density test. To avoid biasing the results (by observing the amount of waste left), an excess of waste was provided (approximately 25 percent greater than each test sample). The samples were gently mixed with the excess material prior to the next determination. The results are found in Table 27 for the 0 psi pressure.

Another experiment was provided to determine the variation of refuse test samples from the same gross sample (R-10 and S-6). Each gross sample was gently mixed and quartered, thus resulting in 8 different test samples. The density and compression analyses were run on each test sample as previously discussed. The results are provided in Figure 44 and Table 27.

The last experiment was to determine the variation of "twin test samples" from the same gross sample. This

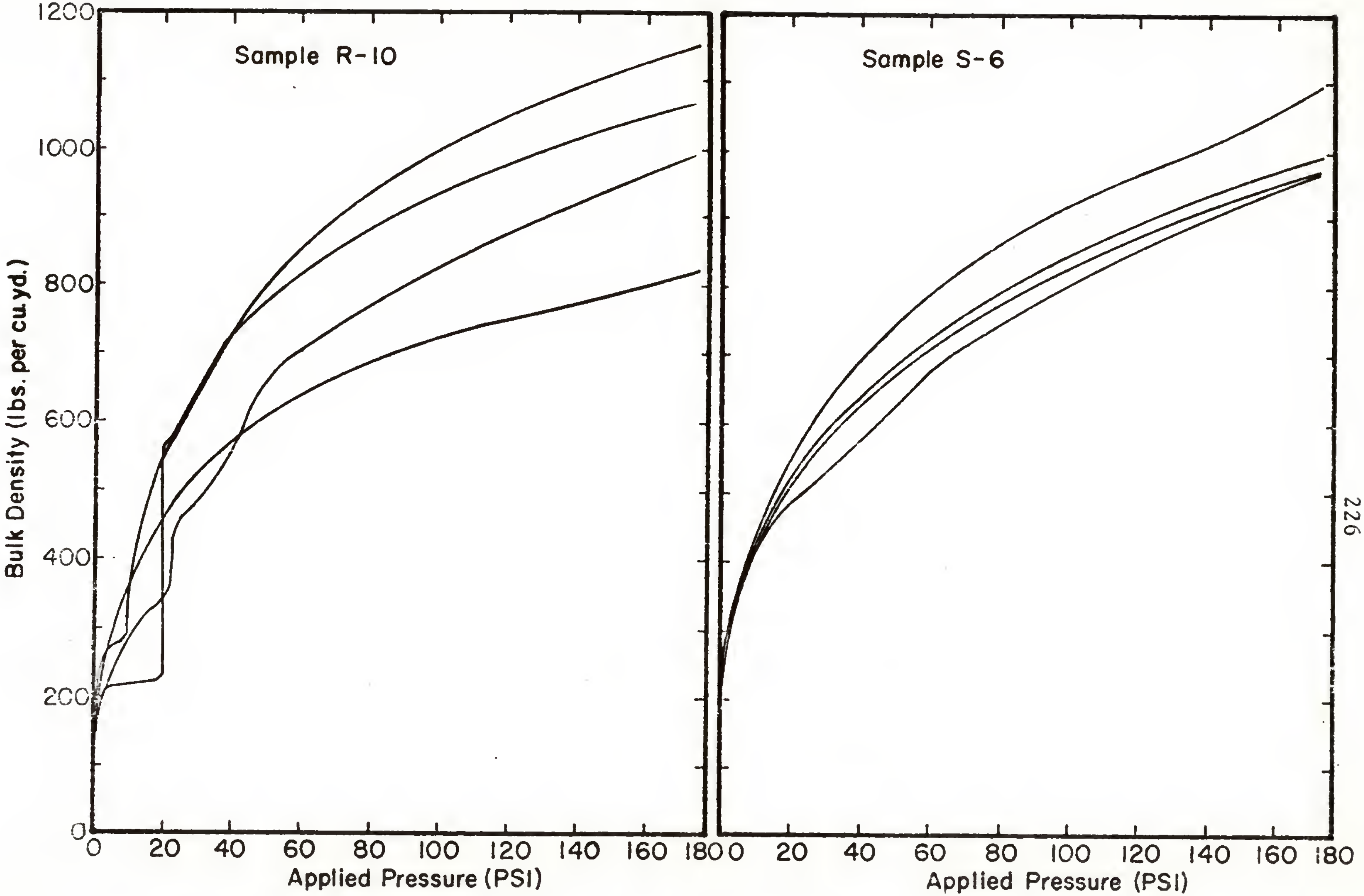


Figure 44. Compressibility of test samples from same gross samples.

experiment consisted of selecting 31 gross samples (raw-10, primary-9, secondary-8, and rasp-4). Each gross sample was gently mixed and two test samples randomly selected, resulting in 31 pairs of test samples. Some of these test samples were duplicate samples of the previous experiment. The samples were analyzed for density and compression as previously explained. The variations of the individual test samples are provided in Table 27. The analyses of variations are provided in Table 28.

A review of the above experiments provides several interesting patterns. First, there were sharp changes in the individual modified raw waste compression curves between 10 and 30 psi (Figure 44). This was due to the sudden collapsing of bottles and cans, drastically increasing the bulk densities. In contrast, the compression curves were smoother for small particle waste. Secondly, the greatest variation was found with the modified raw waste and the least with smaller particle materials, especially rasp waste. The variation was found to increase with increasing applied pressures.

The experimental error of the density analysis (0 pressure) was 1.09 and 0.72 lbs. per cu. yd. for primary and secondary waste, respectively, as indicated by the standard error of means (Table 27). These values were considerably less than the values of the experimental error which included the variations of the samples. For example, the standard error for measuring the density of secondary waste was 8.52, 8.10 and 2.15 lbs. per cu. yd., respectively, for different

Table 28

Sources of Variation of Density and Compression Data

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio
A. 0 psi pressure (loose density)				
Among refuse types	3	169,618.53	56,539.51	33.75
Between twin samples within refuse types	27	45,225.69	1,675.03	5.93
Within twin samples	31	8,751.04	282.49	
Total	61	223,601.26		
B. 10 psi pressure				
Among refuse types	3	612,690.02	204,230.01	56.35
Between twin samples within refuse types	27	97,854.33	3,624.23	1.57
Within twin samples	31	71,553.88	2,308.19	
Total	61	782,098.23		
C. 100 psi pressure				
Among refuse types	3	48,757.24	16,252.41	0.94
Between twin samples within refuse types	25	433,662.39	17,346.50	5.67
Within twin samples	29	88,717.57	3,059.23	
Total	57	571,137.20		

gross samples, twin samples and identical gross samples. Needless to say, these values were considerably greater than the 0.72 lbs. per cu. yd. for experimental error. Thus, the large difference can be attributed to variation in samples.

The experimental error of the compression test could not be partitioned into experimental error due to the testing procedures and experimental error due to the different samples, since it was impossible to analyze the same sample repeatedly. But it was possible to obtain some estimate of the values. First, the most uniform sample can be used as a guide to estimate experimental error. The rasp waste consistently was shown to be the most uniform sample in the particle size analysis (least experimental error). The same result was found for the density and compression data. The rasp waste standard error of means for 10 and 100 psi, respectively, was 7.06 and 9.55 lbs. per cu. yd. These values also included variations of samples.

The analysis of variance also can be used to estimate the experimental error. The 0, 5, 10, 50 and 100 psi pressure data from the twin samples were analyzed, utilizing the randomized complete-block design with unequal subsamples. The tabular analysis of variance of the data for the 0, 10 and 50 psi pressures is provided in Table 28.

The analysis of variance (Table 28) shows a highly significant difference, at the 99 percent confidence level, among different refuse types (except for 100 psi pressure). The data were also highly significant at 5 and 50 psi. The difference between the twin samples (within refuse types) was found highly significant at pressures 0, 5 and 100 psi. The 50 psi pressure was significant at the 90 percent level, while the 10 psi pressure was not found significant. Thus, the twin samples were considered as independent sources of variation and they subsequently were partitioned. The standard error of means were therefore calculated at 3.02, 6.88, 8.63, 9.96 and 10.27 lbs. per cu. yd., respectively, for 0, 5, 10, 50 and 100 psi applied pressures. These pooled values were comparable to the rasp waste values.

The variation of the rebound data also was analyzed at 10 psi pressure. The analysis of variance was used to estimate the experimental error of the twin sample data. The difference among waste types was found highly significant (greater than the 99.5 percent confidence level) while the difference among twin samples within waste types was found significant at the 97.5 percent level. The standard error of means was 10.85, 14.69, 16.54 and 2.92 lbs. per cu. yd. for raw, primary, secondary, and rasp waste, respectively. The standard error was found to be 7.62 lbs. per cu. yd. when the different waste types were pooled. The experimental error for rebound was comparable to the compression data.

CHAPTER VII

DISCUSSION

Particle Size Analysis

Frequency Distributions and Statistical Parameters

The particle size frequency distributions of the composite wastes were presented in Chapter V; each of the component wastes are shown in Figure 45. The cumulative distribution curves of the components and the composite waste were previously presented in Figures 33 to 36. Mathematical functions were fitted to the empirical data and the resulting curves are shown in Appendix I.

As expected, the frequency distributions of the composite wastes were skewed to the right. Skewed distributions are found for most particulate materials [2,25]. This trend has been reported for solid waste by other researchers (see Figures 1-3). The cumulative distributions (Figures 33-36) exhibited the "S" shape, which also is common for most particulate materials.

All composite distributions were found to be bi-modal with the exception of the secondary shredded waste. Such complex distributions are usually a mixture of two or more uni-modal distributions. The bi-modality was expected since

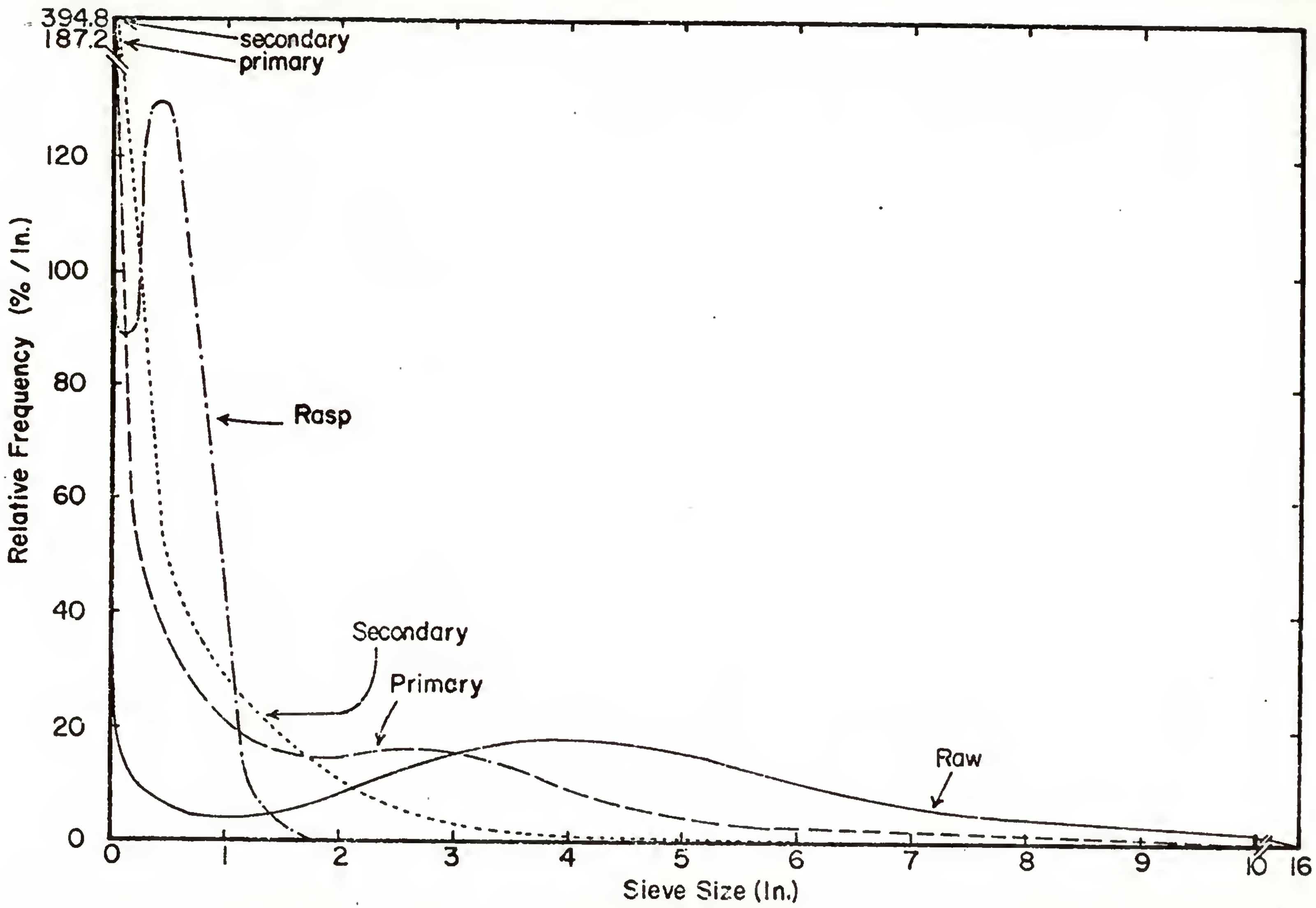


Figure 45. Particle size distributions of composite wastes from Gainesville, Florida, and Johnson City, Tennessee.

solid waste contains various components, each with its own distinct distribution.

The hammermills tended to reduce the waste to log-normal or exponential distributions, as is exhibited by the secondary waste distribution in Figure 45. The exponential or log-normal type distributions were expected, as previous authors [24,26] have reported that grinding or crushing processes produce such distributions. Fess [50] also reported log-normal distributions for primary and secondary hammermill shredded waste (paper, cardboard and glass). The log-normal and exponential distributions were not obtained for rasp shredded waste.

A review of Figure 45 shows several interesting patterns. First, raw waste was the largest particle size waste, while secondary and rasp wastes were the smallest. In addition, successive shredding by the hammermills reduced the particle size (distributions were shifted to the left) and also the right tail of each distribution. Each successive reduction tended to eliminate the "right hump" of the bi-modal distributions and, therefore, more closely approach the expected exponential and log-normal distributions.

The complexities of the composite distributions are presented in Figures 46 to 49, which were plotted from the empirical data. These figures demonstrate how the composite distributions are affected by their respective components. For example, the "hump" in the raw waste (Figure 46) is caused predominantly by paper waste, in addition to glass and

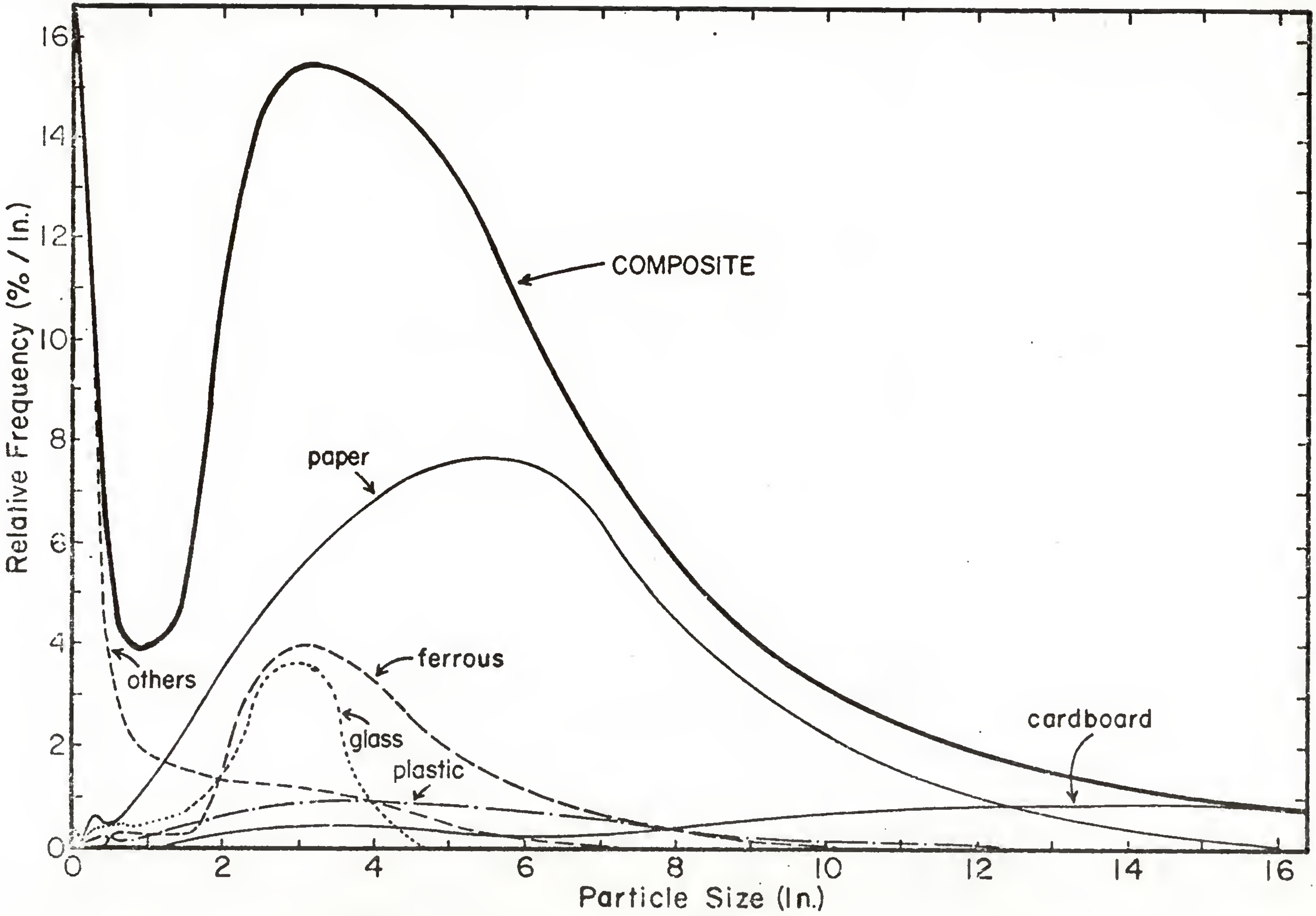


Figure 46. Particle size distributions of raw waste and components from Gainesville, Florida.

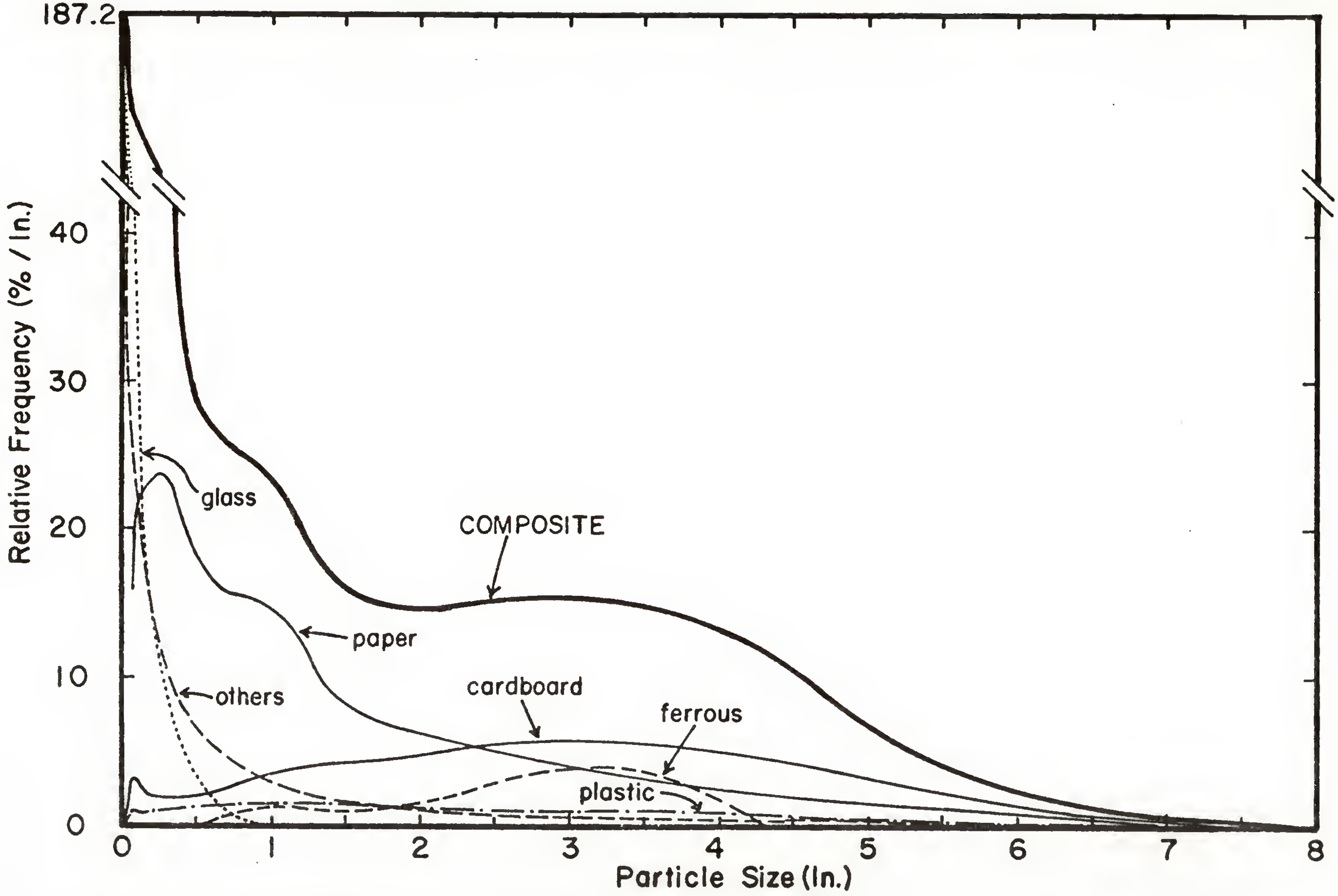


Figure 47. Particle size distributions of primary shredded waste and components from Gainesville, Florida.

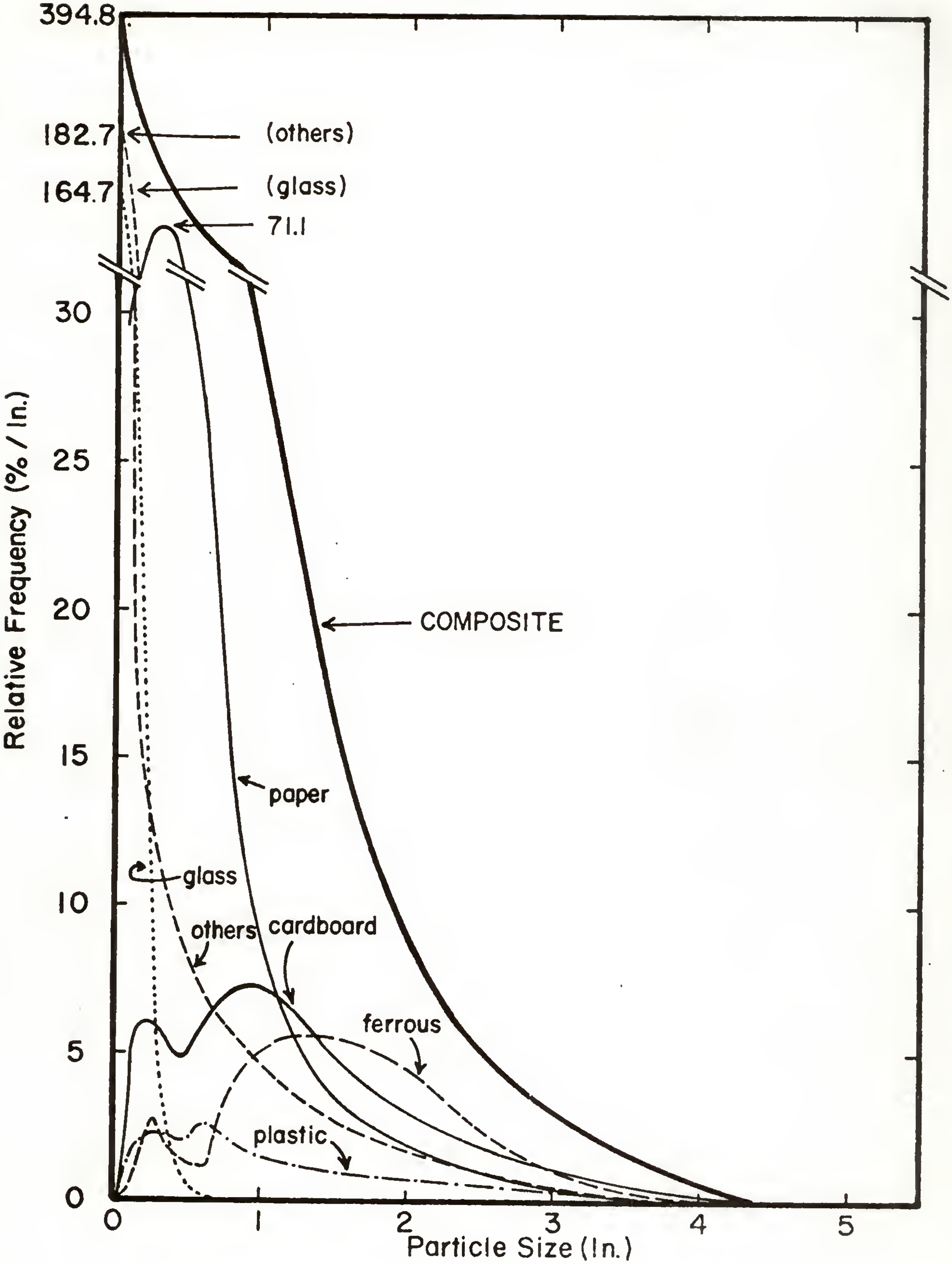


Figure 48. Particle size distributions of secondary shredded waste and components from Gainesville, Florida.

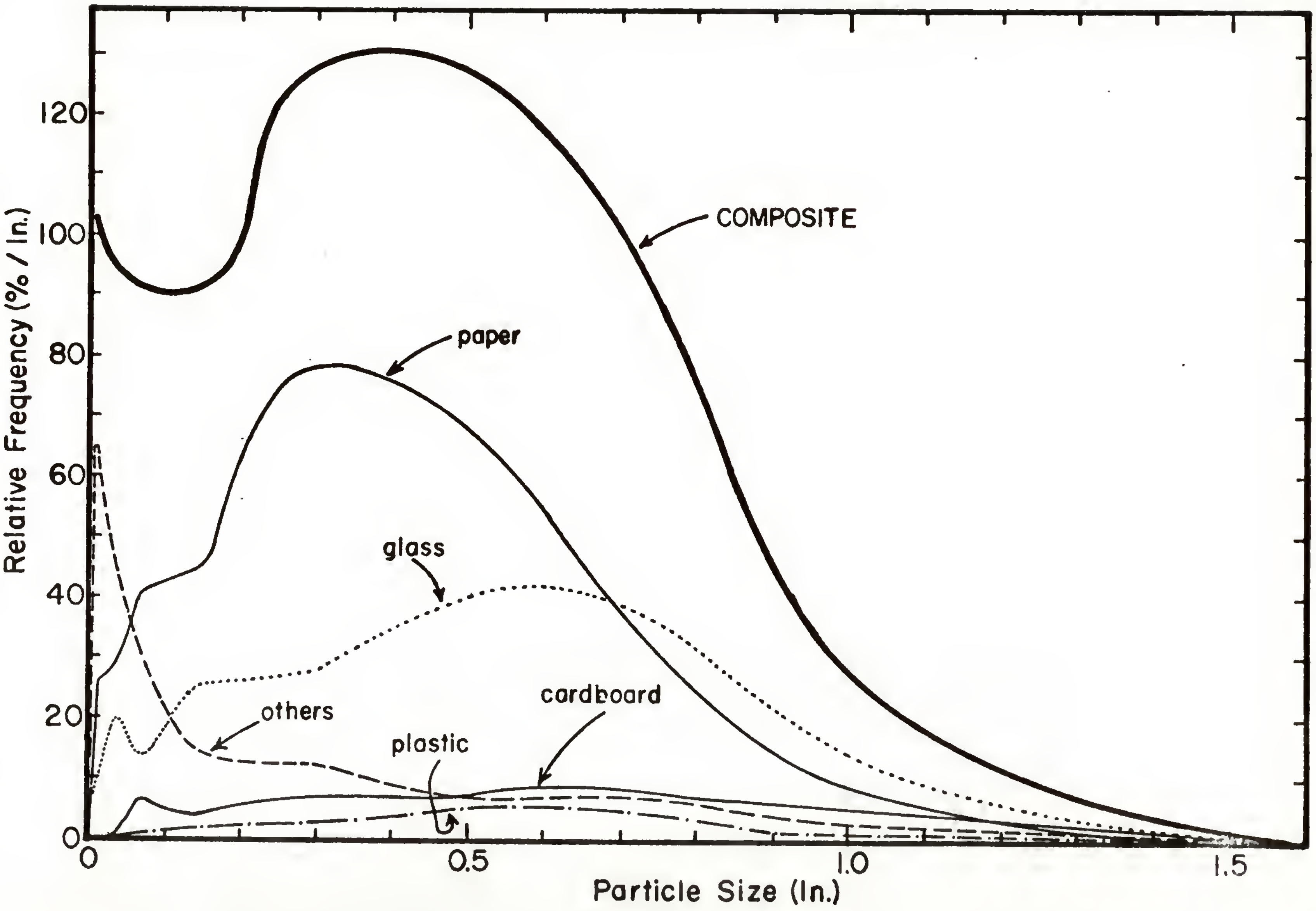


Figure 49. Particle size distributions of rasp shredded waste and components from Johnson City, Tennessee.

ferrous waste. The right tail is produced by cardboard waste, and the left vertical tail is caused by the "Others" component, which is the sum of the smaller percentage components (food, garden, textile, wood, non-ferrous, sand and rock, and miscellaneous waste). The area under the curve of each component distribution reflects its percentage composition, while the area under the curve of the composite waste is the sum of the component areas, or 100 percent. Any point on the composite curve can be found by summing the components, e.g., the location of the composite curve at the 12 in. particle size is the sum of cardboard and paper components, or about 2 percent per inch.

A comparison of the composite cumulative particle size distributions in Figures 33 to 36 presents several interesting patterns. First, shredding has caused each successive composite distribution to shift further to the right (reducing the particle size). Also, the shape of the curve was changed, as successive shredding tended to eliminate the "S" shape and produce a straight line, indicative of a logarithmic distribution. In addition, it represents a well distributed particle size distribution, with a consistent number of particles from the smallest size to the largest (no over-abundance of one particle size). A distinct "S" shape curve was obtained for the rasp composite waste, indicating a non-logarithmic and more uniform particle size distribution.

The composite cumulative particle size distributions found in this research were compared to those found in other research. The cumulative distribution of Gainesville's raw waste was found to be very similar, but somewhat larger in particle size (curve was further to the left) than the raw refuse at London, as presented by Patrick [36] and shown in Figure 1. This was to be expected since the refuse in this country contains a greater quantity of the large particle size paper waste. The cumulative distribution of Gainesville's raw waste was almost identical to the raw refuse found at Cambridge, Massachusetts, as reported by Winkler and Wilson [12, 54] and shown in Figure 8. The only exception was with the larger particle size tail; the Cambridge waste was more skewed. Obviously, Winkler and Wilson were less biased by the large sized items than in this research. Analytical constraints (drying oven size) prevented large particles from being examined in this research. The Gainesville raw waste also was slightly larger than the waste shredded by the Roto-shredder, as reported by Jones [5] and shown in Figure 2.

The cumulative particle size distribution of Gainesville's primary shredded waste was found to be slightly smaller in particle size than the single pass of the flail mill [53], as shown in Figure 2. The particle size of the primary waste was larger than the waste from the shredder with the 6-1/4 in. grate at Madison, Wisconsin (Figure 9), and larger (although the distribution curves were parallel) than the waste from both the Gondard and Tollemache mills, also at Madison (Figure 12). On the other hand, the waste from the secondary hammermill was smaller in size than the waste from both the Gondard and Tollemache mills (Figure 12) and smaller than the waste from the shredder with the 3-1/2 in. grate at Madison (Figure 9).

As was expected, the secondary cumulative particle size distribution was almost identical to the cumulative distribution of the secondary shredded waste as reported by Fess (Figure 3). The primary waste was somewhat larger than the primary waste examined by Fess. The secondary waste of Gainesville also was larger than the waste from the Eidal vertical mill, as reported by Trezek [52] and shown in Figure 2. The distribution curve was located parallel and to the left of the respective Eidal curve. The curve of the cumulative distribution of the rasp waste was located parallel and left of the waste from the small hammermill at Cincinnati, Ohio, as shown in Figure 2 and reported by Oberaker [47].

A comparison of statistical parameters (Table 29) of the various types of raw and processed waste confirms much of the prior discussion. Several additional interesting trends can be noted from this table. First, hammermill shredding tended to increase the coefficients of variation of the particle size distributions. The coefficients of variation for raw, primary, and secondary waste were about 70, 100 and 130 percent, respectively. A 60 percent coefficient of variation was obtained for rasp waste. Apparently, the holes in the rasp (through which the waste must pass) acted as a restriction to eliminate the large particles and thus reduce the variance and coefficient of variation.

Table 29

Statistical Parameters of Various Types of Raw and Processed Waste

Reference Number	Principal Author	Location	Shredders			Mean (in.)	Median (in.)	Standard Deviation (in.)	Coefficient of Variation (%)
			Type	Size (tons/hr.)	Grate Size (in.)				
Raw Refuse									
36	Patrick	London, Great Britain	--	--	--	--	2.92	--	--
--	Ruf	Gainesville, Florida	--	--	--	5.29	4.60	3.33	63
12,54	Winkler	Middlebury, Vermont	--	--	--	9.09	8.15	6.45	71
12,54	Winkler	Cambridge, Massachusetts	--	--	--	5.70	4.85	3.84	67
Shredded Waste									
19	--	Madison, Wisconsin	Hammermill	8	3-1/2	0.75	0.55	0.63	84
19	--	Madison, Wisconsin	Hammermill	8	5	0.96	0.64	0.94	98
19	--	Madison, Wisconsin	Hammermill	8	6-1/4	1.18	0.80	1.14	97
53	--	Sulfur Springs, Texas	Flail mill	24	1 pass	--	1.63	--	--
53	--	Sulfur Springs, Texas	Flail mill	24	2 passes	--	0.73	--	--

Table 29 - Continued

Reference Number	Principal Author	Location	Shredders			Mean (in.)	Median (in.)	Standard Deviation (in.)	Coefficient of Variation (%)
			Type	Size (tons/hr.)	Grate Size (in.)				
49	Fess	Gainesville, Florida	Primary hammermill	30	8x4-1/2 &12x8	--	0.89	--	--
49	Fess	Gainesville, Florida	Secondary hammermill	20	10x3-1/2	0.73	0.38	0.94	129
21	Gawalpanchi	Madison, Wisconsin	Vertical	15	--	0.86	0.7	0.75	87
21	Gawalpanchi	Madison, Wisconsin	Hammermill	8	--	1.08	0.8	0.90	83
51	Jones	Crawford County, Ohio	Roto-shredder	(225 rpm-2 passes)			3.20	--	--
51	Jones	Crawford County, Ohio	Roto-shredder	(225 rpm-6 passes)		--	3.10	--	--
47	Oberaker	Cincinnati, Ohio	Hammermill	small	--	0.35	0.33	0.24	69
37	Rena	Dundee, Great Britain	Hammermill	20	--	1.32	0.98	0.92	70
--	Ruf	Gainesville, Florida	Primary hammermill	30	8x4-1/2 &12x8	2.00	1.46	1.99	100
--	Ruf	Gainesville, Florida	Secondary Hammermill	20	10x3-1/2	0.74	0.38	0.94	133
--	Ruf	Johnson City, Tennessee	Rasp	10	1-1/4	0.47	0.44	0.29	62

Table 29 - Continued

Reference Number	Principal Author	Location	Shredders			Mean (in.)	Median (in.)	Standard Deviation (in.)	Coefficient of Variation (%)
			Type	Size (tons/hr.)	Grate Size (in.)				
52	Trezek	--	Hammermill	0.5	--	--	0.017	--	--
52	Trezek	--	Vertical	2.5	--	--	0.20	--	--
Compost									
49	Fess	Gainesville, Florida	Fresh from digesters and after secondary shredders	--	10x3-1/2	0.50	0.26	0.58	116
49	Fess	Gainesville, Florida	Mature--after fine grind	--	0.56	0.12	0.055	0.14	117

Another interesting trend was that the mean particle size of shredded waste was directly proportional to the shredder grate sizes. To develop this relationship, it was necessary to use the minimum width of the largest grate opening, e.g., 8 in. for the primary shredder grate at Gainesville. The trend is detailed further in Table 30.

Table 30

Effect of Shredder Grate Size on Shredded Waste

Location	Grate Size Parameter (in.)	Mean Particle Size (in.)	Predicted Mean Particle Size (in.)
Gainesville, Florida	8	2.00	1.76
Gainesville, Florida	3-1/2	0.74	0.77
Johnson City, Tennessee	1-1/4	0.47	0.28
Madison, Wisconsin	3-1/2	0.75	0.77
Madison, Wisconsin	5	0.96	1.10
Madison, Wisconsin	6-1/4	1.18	1.38

Linear regression techniques were used to fit an equation to the data. The equation obtained was

$$Y = 0.22\ X \qquad (32)$$

where Y = mean particle size (in.) of shredded waste, and

X = minimum width of the largest grate opening (in.).

This equation was then used to predict the mean particle sizes of the shredded waste listed in Table 30; these values are provided in the same table. The correlation coefficient for the six observations was 0.9898.

The particle size distributions of the components were found to vary, both with the type of components and with the type of shredders. Many other researchers have confirmed this finding [12,32,36,49,50,53,54,56]. The hammermills definitely tended to alter the raw waste to log-normal distributions. The beta distribution predominated with rasp waste. The effect of shredders on each refuse component is shown in Figures 46 through 49 and by the figures in Appendix I.

Each successive shredding tended to shift the distributions further to the left, reflecting the reduction in particle sizes. The shredders also tended to eliminate the "humps" of raw waste and produced log-normal type distributions for the waste from hammermills and beta distributions for shredded waste from rasp mills.

The results of shredding were different for each type of waste component. Previous researchers also have mentioned this [53,55]. In addition, the rasp mill affected certain components differently than the hammermills did (see Table 31).

Glass waste was the easiest material for the hammermills to reduce. The mean particle size of the raw glass waste was reduced 94.1 percent by the primary shredders. The glass from the rasp mill was considerably coarser. Food and garden wastes were readily reduced by both the primary hammermill

Table 31

Size Reduction of Waste Components by Different Types of Shredders

Waste Component	Mean Particle Size Reduction by Shredding (% of raw waste)		
	Primary Shredder	Secondary Shredder	Rasp Mill
Food	79.2	77.5	81.0
Garden	86.8	88.5	91.4
Cardboard	69.4	86.9	94.7
Other paper	68.0	91.2	92.6
Plastic	57.0	64.2	89.2
Textiles	6.7	57.9	84.9
Wood	68.7	85.3	82.5
Ferrous	33.4	60.0	76.2
Non-ferrous	18.5	58.4	79.7
Glass	94.1	97.1	80.7
Sand & rock	75.9	91.5	39.3
Composite	62.2	86.0	91.1

and the rasp. Textile waste was the hardest to reduce by the hammermills. The primary shredder reduced it only 6.7 percent and the secondary shredder reduced it further to 57.9 percent of raw waste. The rasp did not have as much difficulty reducing textiles, as this component was reduced 84.9 percent. Metals also were difficult to reduce by hammermill shredders, as ferrous and non-ferrous wastes were reduced to 33.4 and 18.5 percent, respectively, by the primary hammermill. The numerical value for the reduction of metals in the rasp mill is misleading, because most metals were not allowed to pass through this shredder. The plastic waste also was difficult to reduce as reflected by the 64.2 percent reduction accomplished by the combination primary-secondary shredding.

Several interesting points are shown by the particle size distribution in Appendix I and the cumulative distribution shown in Figures 33 to 36. Many components are concentrated in specific size ranges. This is apparent as many metal and glass containers are very similar in size. Thus, it appears industrial screens can be feasibly used to remove and/or concentrate these materials. For example, about 50 percent of sand and rock can be removed with the No. 30 sieve although other components will be removed to a minimum extent. Thus, it could be feasible to reduce maintenance costs or increase product quality. In addition, glass, ferrous and non-ferrous wastes were found to be concentrated in the 2- to 4-in. particle size range as 86.4, 62.7 and 68.8 percent of the total weight of each component, respectively, were found in this range. This represented 23.9, 25.4 and 1.9 percent of the total weight of material in this size range. Thus, two screens (4 and 2 in.) could effectively increase the concentrations of these components by two to three times. Further concentrations were possible if the proper size screens had been used.

Similarly, Winkler and Wilson [12,54] reported that metal objects comprised up to 40 percent of the total refuse in the 3-to 5-in. size range as opposed to only 9 percent for refuse of all sizes. Also, they mentioned that glass objects accounted for 38 percent by weight of refuse in the 5-to 10-in. range.

The particle size distributions of the components for raw waste were found to be consistently less than the distributions presented by Winkler and Wilson [12,54] and shown in Figure 16. Obviously, a major part of the difference can be expected by the drastically different methods utilized in measuring the particles and defining the particle size. Winkler and Wilson defined the particle size by the longest length of the object. In addition, some difference can be expected, as objects less than one inch in size were neither measured nor classified.

A comparison of the statistical parameters developed by other researchers for different types of components for raw and shredded wastes is shown in Table 32. The median particle size was used and values were obtained directly from previous tables or cumulative distributions. It was necessary to estimate the median particle size from the work of Winkler and Wilson [12,54] as shown in Figure 16.

Table 32 explicitly shows the difference between Winkler and Wilson's research and this research, resulting from the method of specifying the size of raw waste. In contrast, close results were obtained for many shredded waste components reported by Fess, Stirrup and Oberaker. Similar cumulative distributions also were obtained in this research.

Table 32

Statistical Parameters of Different Types of Raw and Shredded Waste Components

Reference Number	Principal Author	Median Particle Size (in.)			
		Raw	Single Hammermill	Rasp	Twice Shredded
Food					
--	Ruf	0.56	0.40	0.35	0.39
12,54	Winkler	8			
Garden					
49	Fess		0.08		0.09
--	Ruf	0.42	0.09	0.08	0.09
Total paper					
49	Fess		1.3		0.65
50	Fess		1.40		0.59
--	Ruf	6.34	1.78	0.42	0.54
12,54	Winkler	12			
Cardboard					
50	Fess		2.78		1.43
--	Ruf	11.03	2.93	0.53	1.13
Other paper					
50	Fess		1.02		0.43
--	Ruf	5.55	1.07	0.41	0.35
Plastic					
--	Ruf	4.72	2.17	0.55	1.08
12,54	Winkler	9			
Textile					
--	Ruf	3.76	3.82	0.57	1.37
12,54	Winkler	13[a]			
Wood					
49	Fess		1.3		0.4
--	Ruf	2.31	0.72	0.60	0.37

Table 32 - Continued

Reference Number	Principal Author	Median Particle Size (in.)			
		Raw	Single Hammermill	Rasp	Twice Shredded
Ferrous					
49	Fess		1.8		
--	Ruf	3.57	2.80	0.90	1.49
32,56	Stirrup		2[b]		
Total metals					
--	Ruf	3.53	2.76	0.67	1.45
12,54	Winkler	5			
Glass					
49	Fess		0.09		0.04
50	Fess		0.13		0.06
57	Oberaker		0.06	0.47	0.05
--	Ruf	2.84	0.11	0.54	0.05
32,56	Stirrup		0.03		
12,54	Winkler	8			
Sand & rock					
49	Fess				0.03
--	Ruf	0.06	0.03	0.15	0.02

[a] Includes rubber and leather.

[b] Tin cans only.

Analysis of Variance

The variation of refuse samples contributed significantly to the different particle size distributions. The major reason for this variation was due to changes in the waste components. Gawalpanchi et al. [21] reported a significant difference in size distributions due to variations in refuse composition.

The largest variation was found with the larger particle size waste and at the larger particle size end of the raw cumulative distribution curve. The least variation was found with the rasp waste. The coefficient of variation of the mean particle size for raw, primary, and secondary waste was found to be 2.13, 1.71 and 1.25 percent, respectively. With the exception of raw waste, the experimental error was nearly constant at all points along the cumulative distribution curve.

Gawalpanchi et al. [21] also found that the experimental error was nearly constant at all points along the cumulative distribution curve. They determined the coefficient of variation at the 1.0, 0.5 and 0.185 in. size of the cumulative distribution curves. Their average value, 3.82 percent, was considerably greater than found in this research. Obvious reasons for the larger values were that their experimental error included sampling error and the use of considerably smaller test samples (0.13 to 0.22 lbs. versus 1.35 to 16.55 lbs.). The different methods in determining the experimental error (cumulative distribution curve versus the mean) should not be a factor, since the experimental error was constant for both studies at all points along the curve.

The classification technique was found to be relatively reproducible. Low experimental errors were obtained. The coefficient of variation was found to be greater for fine particle materials and low percentage components.

Shredding definitely was shown to reduce the particle size. The mean particle size between the various refuse types (raw vs. primary, primary vs. secondary, and secondary vs. rasp) was shown to be significantly different. The rasp produced a smaller particle material.

Predicting Particle Size Distributions and Statistical Parameters

The division of the composite wastes into their components provides a powerful tool for predicting particle size distributions and statistical parameters for other composite wastes. This is based on the laws of mixing distributions and requires knowledge of the individual components (or mixes). It is assumed that each component type distribution is identical and only the mixture of the components varies (or different compositions). This assumption appears to be reasonable since the major difference within waste types has been their varying composition and not different component distributions.

The methodology of predicting particle size distributions requires knowledge of the individual particle size distributions, as well as the percent composition of each component.

A condition of the composite frequency distribution is that the component frequencies add up to the total number in the sample, or 100 percent if probability distributions are used [24,133]. This relationship can be written as follows:

$$f(Y_T) = \sum_{\text{all } j} W_j \, f(Y_j)/W_T \tag{33}$$

where j = index number of the waste component,

$f(Y_T)$ = particle size distribution of the composite waste,

$f(Y_j)$ = the particle size distribution of the j^{th} component,

W_j = percent composition of the j^{th} component, and

W_T = the sum of the W_j's (normally 100 percent).

The equations of the particle size distributions of the components, e.g., $f(Y_j)$, are contained in Appendix I.

The above methodology was used to predict the distribution of each composite waste type (raw, primary, secondary and rasp), using the compositions found for each component (Appendix H). The mean and median particle sizes were calculated from the distribution data and the predicted distributions compared to the empirical distributions. The index of correlations between the empirical and theoretical distributions also were calculated for each waste type. A very high index of correlation was obtained for each waste type as shown in Table 33. The statistical parameters were very close.

Table 33

Comparison of Theoretical with Actual Composite Distributions

Waste Type	Index of Correlation	Mean (in.)		Median (in.)	
		Theoretical	Actual	Theoretical	Actual
Raw	0.9934	5.1621	5.2918	4.4706	4.5984
Primary	0.9908	2.0445	2.0004	1.4440	1.4558
Secondary	0.9909	0.7366	0.7432	0.3567	0.3750
Rasp	0.9830	0.4491	0.4719	0.4152	0.4446

The above methodology also can be used for undried refuse, using wet weight composition data. This is because the moisture content from particle to particle is relatively uniform for a particular refuse component.

The empirical composite distributions shown in Figure 45 have different compositions. Thus, the particle size differences between the composites are reflected by the varying compositions. Therefore, it was decided to utilize equation (33) to standardize the waste types so that each composite had the same composition.

The composite mixture which was utilized was the weighted average (by the weights of samples) of Gainesville's waste, since each of Gainesville's waste types (raw, primary and secondary) is an estimate of the true refuse composition. The weighted average composition is provided in Table 34.

Table 34

Weighted Average Composition of Waste from Gainesville, Florida

Waste Component	Weighted Composition (%)
Food	4.4941
Garden	2.2780
Cardboard	11.8294
Paper	46.3568
Plastic	5.0691
Textile	2.4957
Wood	1.8396
Ferrous	11.8514
Non-ferrous	1.0205
Glass	9.7882
Sand and rock	2.7925
Miscellaneous	0.1848
Total	100.0000

These compositions were used with the component distribution equations (Appendix I) to predict waste types for materials of identical composition. Distributions very similar to those shown in Figure 45 were obtained. Most of the changes were on the small particle size ends of the distributions. As expected, very little change was noticed for Gainesville's waste since the weighted average composition was very similar to the composition of each waste type. The distribution of the rasp waste was slightly more peaked and shifted to the left; in addition, it was uni-modal.

The statistical parameters of the standardized distributions were calculated from the distribution data and compared to the empirical composite distributions. The data are provided in Table 35. Very small changes were obtained.

Table 35

Comparison of Standardized (Same Composition) and Empirical Composite Distributions

Waste Type	Mean (in.)		Median (in.)	
	Standardized	Actual	Standardized	Actual
Raw	5.1621	5.2918	4.4706	4.5984
Primary	2.0445	2.0004	1.4440	1.4558
Secondary	0.7366	0.7432	0.3567	0.3750
Rasp	0.4491	0.4719	0.4152	0.4446

Equation (33) also can be used to predict the mean (or median) particle size of a composite distribution, utilizing the mean (or median) particle sizes of the components. Thus, it is not necessary to calculate these statistical composite values from the distribution data. As before, the composition of the waste components is represented by W_j; the difference is that the mean particle size (or median) is represented by $f(Y_j)$.

A similar equation can be used to calculate the variance of the composite distributions, as shown below [24]:

$$S_T^2 = \sum_{\text{all } j} W_j(S_j^2 + \bar{x}_j^2)/W_T - \bar{x}_T^2 \tag{34}$$

where j = index number of the waste component,

S_T^2 = variance of the composite waste,

S_j^2 = variance of the j^{th} component waste,

W_j = percent composition of the j^{th} component,

W_T = the sum of the W_j's (normally 100 percent),

$\bar{x}_j$ = mean particle size of the j^{th} component, and

$\bar{x}_T$ = mean particle size of the composite (calculated as indicated above with equation (33)).

Similar methodologies can be used to predict particle size distributions and statistical parameters of waste processed by different waste systems. First, the particle size distributions and parameters of waste shredded by identical shredders can be directly obtained, as indicated previously.

Different shredders will provide different results, because of the different size shredder grates. The effect of different size shredder grates was discussed previously in this chapter. It was indicated that the mean particle size of shredded waste was linearly proportional to the minimum width of the largest shredder grate. In addition, similar type shredders tend to produce similar shaped distribution curves (e.g., rasp versus hammermill), especially for the components. Thus, these relationships can be used to predict refuse particle size distributions from different shredders.

The particle size gradation of processed waste can be predicted when most of one or more components have been removed, e.g., when ferrous material is removed by magnets. In this case, equation (33) is still used but W_x, the composition of the modified component, is reduced accordingly. In addition, W_T is now the sum of the remaining components, or something less than 100 percent.

In a similar fashion, equation (33) can be used when certain size fractions have been removed by screens. In this case, the removed size fractions are eliminated from the composite curve and the composite function is divided by the percentage of remaining material, so the area under the modified curve adds up to 100 percent.

Density and Compression Analysis

Loose Bulk Density Analysis

The loose bulk density of each waste type was directly obtained from the initial compression test results (zero pressure) and is shown as the second column of Table 36.

Table 36

Loose Bulk Density of Various Waste Types

Waste Type	Dry Weight Loose Bulk Density (lbs. per cu. yd.)	Wet Weight Loose Bulk Density (lbs. per cu. yd.)
Raw	98.7	141.0
Primary	84.1	120.1
Secondary	136.5	195.0
Rasp	256.6	366.6

The loose densities generally followed an expected pattern: greater densities were obtained for the finer sized particles. The only discontinuity was between the raw and primary waste types, where a larger value was obtained for the larger particle size raw waste. Perhaps much of this difference can be attributed to the different average compositions of each waste type. For example, raw waste had considerably more of the heavier food and metal components (Table 14), while the primary waste had a significant quantity of the lighter cardboard waste. The composition of each waste type is found in Appendix H. To some degree, the larger loose bulk density for rasp waste can be attributed to the composition. Rasp waste had a considerable quantity of glass, 30.3 percent, while the weighted average composition of glass for Gainesville's waste was only 9.8 percent.

The above results were compared to other values (see Table 12). The values from Table 12 were found to be consistently greater. This was expected since other researchers did not dry their samples. Also, the "loose state" in this research is somewhat different than the "loose state" defined by others. This is because: (1) refuse in containers usually had some compression and consolidation due to the method of filling the containers, larger waste volumes (greater thickness), and longer periods of retention, and (2) waste in the open bed trucks had some compression due to motion vibration and the desirability to obtain large truck loads.

The above results were adjusted to a wet weight basis to compare them to the other research results reported. The adjusted values are found in the last column of Table 36. A moisture content of 30 percent (wet weight basis) was used to approximate the national average. The general equation used for this adjustment was:

$$M = \frac{100\ W}{W + S} \tag{35}$$

where M = moisture content (percent),

W = weight of water, and

S = weight of solids.

Another form of this equation can be used:

$$W + S = \frac{100\ S}{100-M} \tag{36}$$

This equation was used to adjust the values in Table 36. These values were still considerably below the comparable data in Table 12.

The added moisture also will increase the density due to the extra pressure applied by weight of the water. Some 36 to 110 lbs. of moisture were theoretically added to each cubic yard of waste. This is the equivalent of pressures ranging to a maximum of 0.08 psi. Thus, slightly greater values are expected.

The increase in theoretical moisture content was not expected to reduce the compressive strength of the particles, and increase the bulk density. This is because most of the solids are still relatively dry at 30 percent moisture content.

A much greater moisture content is required to reduce the particle strength of the major solid waste components, e.g., paper and cardboard. Also, the compressive strength of many other components are not affected by moisture (metals, glass, plastic, wood). In addition, there is not enough water available at 30 percent moisture content to act effectively as a lubricant between the particles.

Compression Curves

The compressibility values of the various types of waste were presented in Figures 40 to 43. These figures are reproduced for comparative purposes as Figure 50. They represent the compressed densities obtained for the various pressures used in the study.

Several interesting trends may be noted from these curves. First, the curves did not indicate elasticity, as the data did not obey Hooke's Law, i.e., stress is proportional to strain. The curves were found to be concave functions of the logarithmic type, as reported also by most other researchers (Figure 23). The slope of each curve decreased with increased applied pressures from an initial point representing the loose bulk density (zero pressure).

The curves exhibited greater compressed densities with decreased particle size. With the exception of raw waste, the other curves were parallel to each other, with the finer particle wastes having greater densities. These findings are comparable to those reported by other researchers (see Chapter

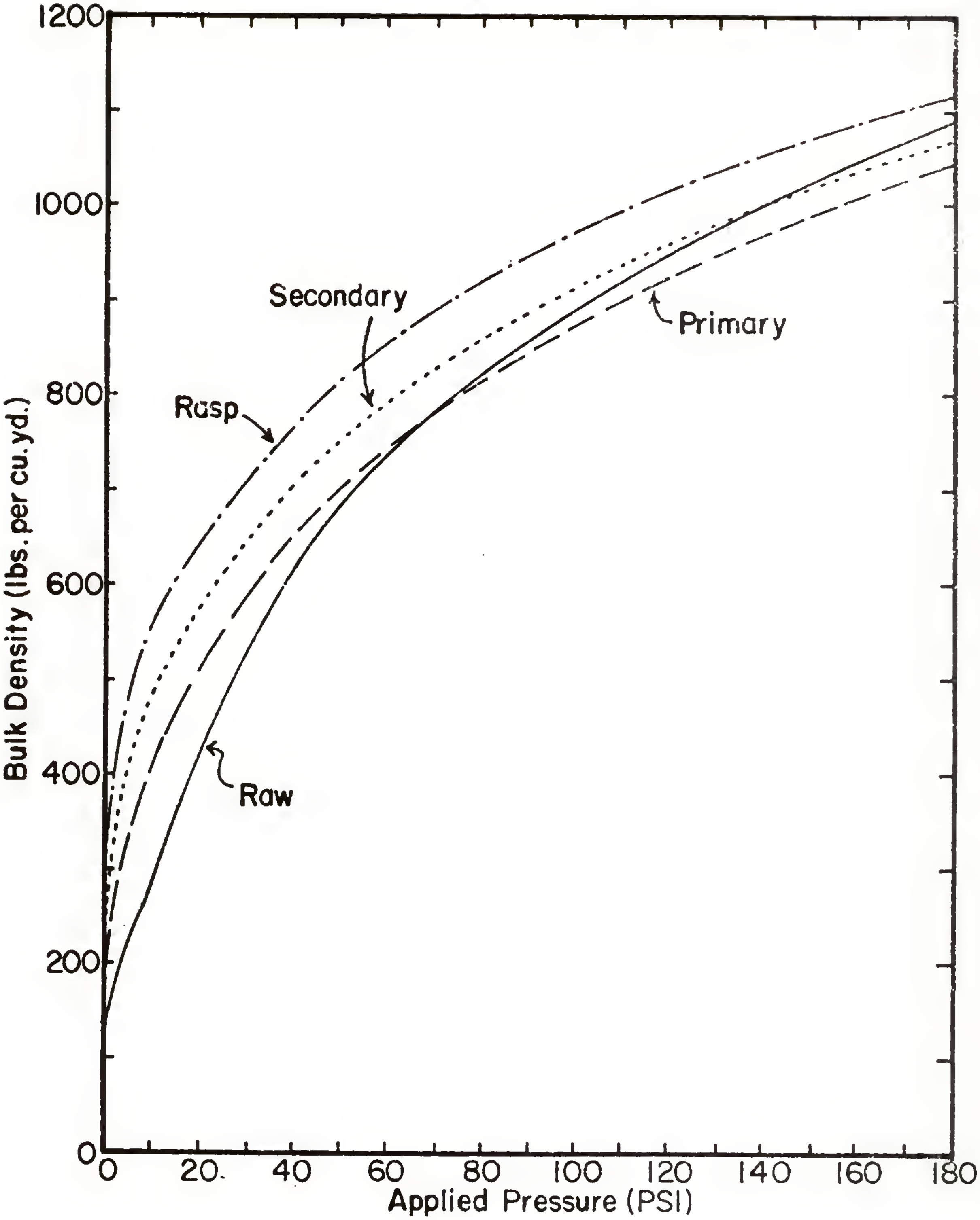


Figure 50. Compressibility of various types of waste.

IV). The curves tended to converge at greater pressures as the spread of density values decreased to about one-fourth of their spread at 10 psi pressure. This was expected since the difference of compression due to particle sizes should be minimized by greater pressures.

Raw waste did not completely follow this trend. At low pressures, the curve was reasonably predictable by the above relationship, but it diverged from it at higher pressures. The raw refuse compression curve crossed both the primary and secondary waste curves at about 65 and 125 psi pressures, respectively. Apparently, factors other than pressure and particle size are also important in determining the compressed density.

One factor could be the standard deviation of the waste. A high standard deviation infers that the waste is well distributed and has a wide spread of particle sizes. Thus, smaller particles could fill the voids between the larger particles, subsequently increasing the density as the pressures are applied. This appears to be plausible, since a larger standard deviation was found for raw refuse (Appendix H). However, if this was completely correct, one would expect the initial density to be greater. In addition, one would expect similar characteristics between the other wastes, as the standard deviation varies considerably between these waste types.

Another important consideration (which is perhaps the predominant reason) is that the compression curve of the raw waste was only approximate, due to its large variation at higher pressures (Figure 40). The raw waste compression curve was established with only 10 samples. If more samples were analyzed, it is likely that the curve would be lowered below the primary compression curve. The raw waste compression curve could be below the primary curve at 55 percent confidence limits and at the higher pressures.

The values of the compressed waste ranged from the loose densities to a high of 1,118 lbs. per cu. yd. at the highest pressure (174.7 psi). The lowest density noted at the highest pressure applied was 1,041 lbs. per cu. yd. for primary waste.

The compression curves compared favorably to the compression curves reported by others after all data were corrected for moisture. On a dry weight basis, all of the curves developed during the study were consistently below all of the curves reported by other researchers (Figure 23), in the respective pressure range. However, when the data were altered for 30 percent moisture content (dry weight basis) using equation (36), the complete length of the rasp curve was almost identical to the results obtained by the American Baler Company study [106] and by the Public Health Service study at Chandler, Arizona [4,74]; the other curves were slightly below them. For example, at 100 psi pressure, a density of 1,310 lbs. per cu. yd. was obtained for secondary shredded waste corrected to 30 percent moisture. A value of

1,400 lbs. per cu. yd. was obtained from the American Baler Company curve.

Rebound Analysis

The springback or rebound tendency of refuse is shown in Figures 40 to 43. The percent expansion of each waste type after three pressure loadings (5.0, 10.2, and 174.7 psi) is presented in Table 37. This table provides the expansion after the pressure was released, as compared to the volume of compacted refuse under the maximum applied pressure. The loading was released to 0.7 psi only, due to analytical constraints. An additional rebound reading also was obtained for the 174.7 psi rebound and is indicated in the table. The rebound measurements were taken about one minute after the release of the pressure loading was started.

Table 37

Expansion Characteristics of Compressed Waste

	Percent Expansion (after designated pressures were removed)			
	Pressures (psi)			
Waste Type	5.0	10.2	174.7	
	Rebound Pressure			
	0.7	0.7	4.1	0.7
Raw	5.33	9.89	18.86	43.80
Primary	15.38	18.82	19.43	55.32
Secondary	10.29	16.20	18.68	40.22
Rasp	5.70	9.97	11.40	26.16

Several trends are suggested by the data in Table 37. First, the expansion was less (except for raw refuse) for smaller particle sized waste. This was true at all pressures. The expansion ranged from 5.33 to 15.38 percent after 5.0 psi and 26.16 to 43.80 after the 174.7 psi pressures were obtained. These figures compare favorably to the APWA study [107] in which expansions of 50 to 60 percent were obtained two minutes after applied pressures of 3,000 to 3,500 psi were reached. They were considerably above the 6 percent reported by Smith [122] at San Diego, but the springback found there was limited because the bales were tied with wire.

Less springback was observed when the compacted refuse was constrained at a slightly higher pressure (4.1 vs. 0.7 psi), as shown in the table. The expansion at 4.1 psi was less than half of that obtained at 0.7 psi.

The expansion also increased as applied pressures increased. For example, the expansion of rasp waste was 5.70, 9.97 and 26.16 when the compressed refuse pressures were released from 5.0, 10.2, and 174.7 psi, respectively, to 0.7 psi.

Another interesting point was that the raw waste exhibited the lowest expansion characteristics at low applied pressures (5.0 and 10.2 psi), but at the 174.7 psi pressure its expansion was high. The reason for this change is not clear, but it appears to be associated with the collapsing containers which occurred at about 20 psi pressure.

Model Fitting and Correlation with Particle Size Statistical Parameters

A statistical model was fitted to the compression data to determine the correlation of the compression data to the particle size statistical parameters. UCLA's BMDO2R multiple stepwise regression computer program was used [136]. Two models were fitted, one from the applied compression data and the other from the rebound data.

From previous experience, there appeared to be three main types of variables which would affect both the compression and the rebound densities: (1) the applied pressure, (2) particle size distribution data, and (3) the refuse composition data.

Several forms of the statistical model were indicated by the curves shown in Figure 50. First, the curve begins from the loose density, thus requiring a constant for the equation. Secondly, the equations must have a log-normal or exponential form, in order to provide the primary shape. Thirdly, since the compressed densities were affected by the particle size, a particle size factor must be added. This third factor must be divided by the applied pressure in order for the curves to converge as the pressure increases. A constant also must be added to this pressure term to prevent the third factor from exploding to infinity at zero pressure. Since there is interaction between the mean particle size and the distribution standard deviation, the best form of the particle size parameter appears to be their product. Lastly, the information in Table 11 indicated that the refuse composition was important. Therefore, a fourth factor was added to account for this, e.g., the summation of the lighter components.

Therefore, fourteen independent variables were used in each program. Eleven represented the refuse composition; one was the applied pressure; and two were particle size parameters (mean and standard deviation).

Approximately 50 transformations were provided for each model, in order to account for non-linearity, interactions, and the summation of several components. Some 210 observations were used in fitting the compression model and 120 were provided for the rebound. The selected observations for the compression model were the densities at the initial pressures of 0, 10, 50, 100 and 174.7 psi. Three densities at pressures of 0.7 psi were used for the rebound model. Each observation consisted of the dependent variable (density), and the 14 independent variables.

The final results of the compression model were very complex, requiring 13 steps and having 11 variables. The multiple regression coefficient was 0.9836 and the standard error of estimate was 65.17 lbs. per cu. yd. Those variables which increased the multiple regression coefficient only slightly were eliminated. Thus, the equation was reduced to

$$Y = -180.9 + 615.30 \log(x_1+6) - 7673 \frac{\log x_2x_3}{x_1+80}$$

$$- 2.419(x_4+x_5+x_6+x_7) \qquad (37)$$

where Y = dry weight density (lbs. per cu. yd.),

x_1 = applied pressure (psi),

x_2 = mean particle size (in.),

x_3 = standard deviation of the particle size distribution (in.),

x_4 = percent composition of garden component,

x_5 = percent composition of cardboard component,

x_6 = percent composition of paper component, and

x_7 = percent composition of wood component.

This equation was provided by only three steps of the multiple regression program, and the multiple regression coefficient was 0.9798. The standard error of estimate was 70.82 lbs. per cu. yd. The most important variable was $\log(x_1+6)$, as a multiple regression coefficient of 0.9680 was obtained with it. The second variable (particle size parameters) increased the coefficient by 0.0081; the refuse components increased it an additional 0.0037.

It was decided to plot this equation using Gainesville's average waste (Table 34). The equation is then reduced to

$$Y = -331.6 + 615.30 \log(x_1+6) - 7673 \frac{\log x_2x_3}{x_1+80} \qquad (38)$$

The plotted equation is found in Figure 51 for different values of x_2x_3.

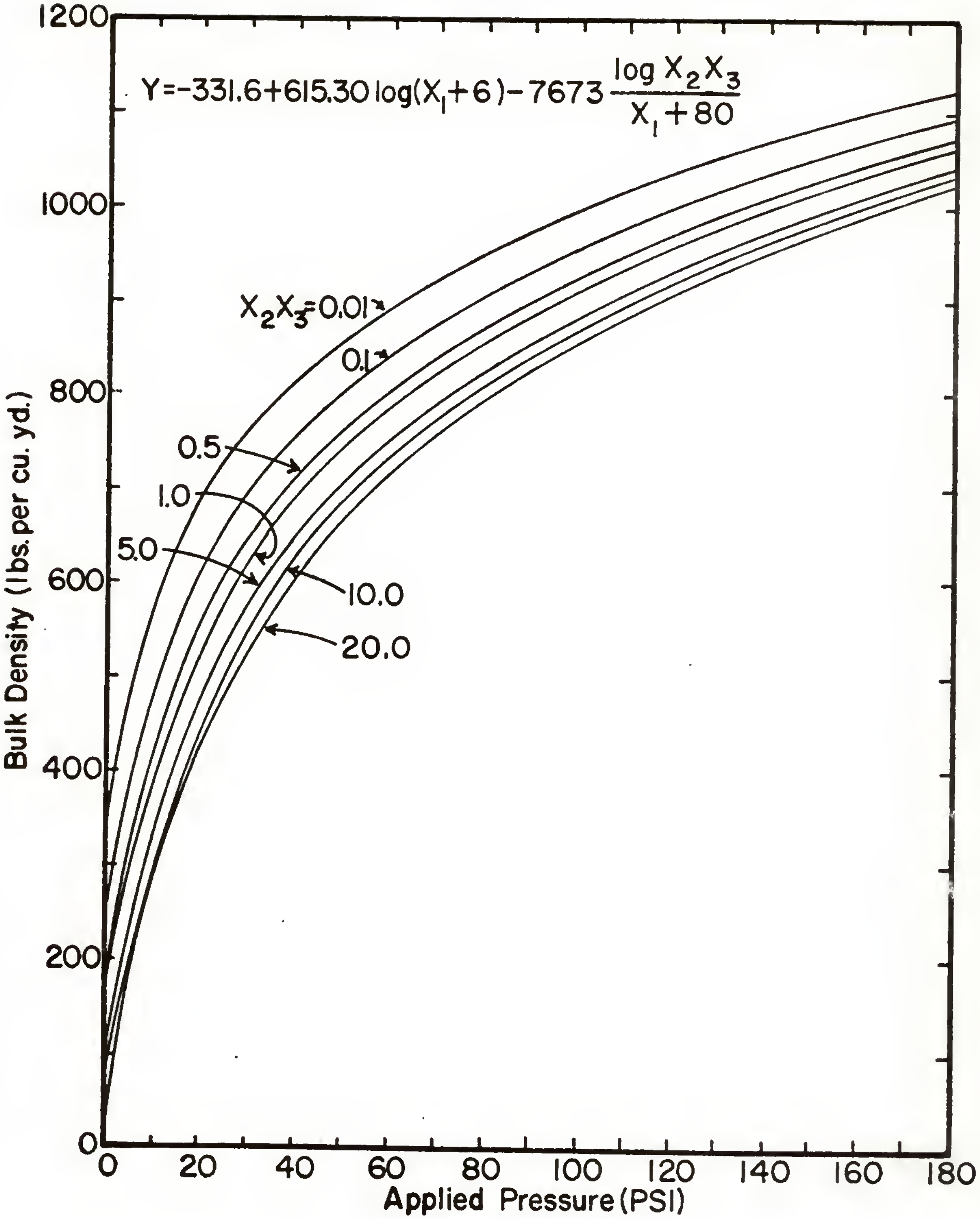


Figure 51. Mathematical model of compression data.

A review of the curves in this figure indicates several interesting points. First, the curves had identical shapes to the empirical curves with greater densities for larger particle size waste. The particle size distribution was defined as x_2x_3, the product of the mean and standard deviation. Although the curves did not cross, they did converge at high pressures.

A similar equation also was provided for the rebound data, as shown:

$$Y = 262.7 + 95.85\ x_1^{0.35} - 748.8\ \frac{\log\ x_2x_3}{\sqrt{x_1+30}} - 1.525(x_4+x_5+x_6+x_7) \qquad (39)$$

The variables are the same as for equation (37).

The above equation also was provided by three steps and the multiple regression coefficient was 0.9445. The standard error of estimate was 73.45 lbs. per cu. yd. The most important variable was $x_1^{0.35}$, as a multiple regression coefficient of 0.8948 was obtained with it.

The second variable (particle size parameters) increased the coefficient by 0.0456; the refuse components increased it an additional 0.0041.

Using Gainesville's average waste, the equation was reduced to

$$Y = 167.7 + 95.85\ x_1^{0.35} - 748.8\ \frac{\log\ x_2x_3}{\sqrt{x_1+30}} \qquad (40)$$

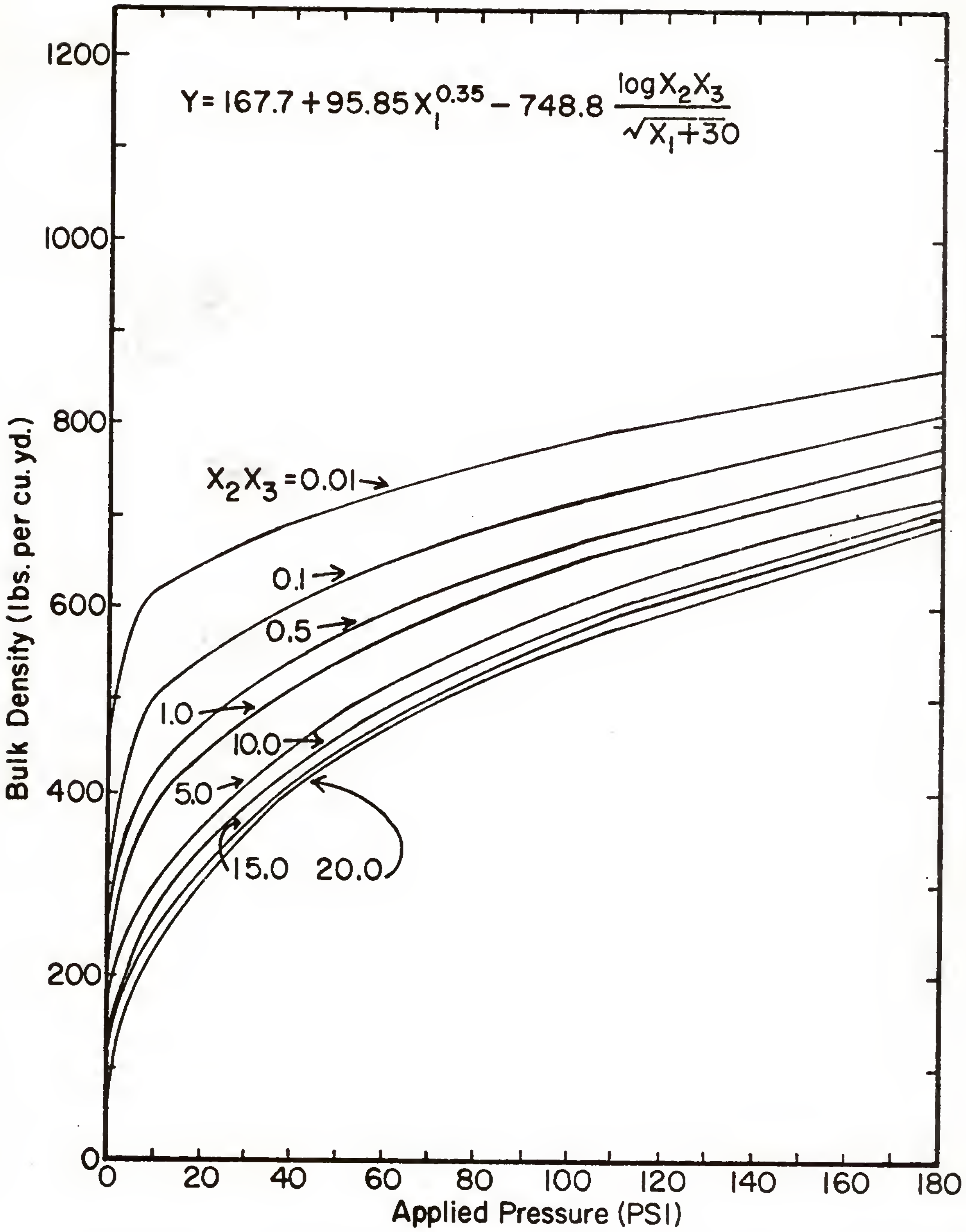


Figure 52. Mathematical model of rebound compressive data.

The plotted equation is shown in Figure 52 for different values of x_2x_3. The curves in this figure are very similar to the previous curves, but they are more dispersed and have lower bulk density values.

The model was used to predict the densities of various types of refuse, using the average refuse composition and particle size data found in Appendix H. The theoretical curves are plotted in Figure 53 and are notated as Raw_T, Primary_T, etc. For comparative purposes, the actual empirical curves (Figure 50) also have been plotted and are notated by Raw_A, Primary_A, etc.

A comparison shows that the model is very accurate. Good results were obtained for primary and secondary waste. The greatest variation was with the raw waste, especially at high pressures. Nevertheless, the models can be used to predict densities within the applied pressure range (0 to 174.7) and beyond. The accuracy of the model decreases as the pressure increases beyond its limits. Both equations can be modified with equation (36), if the final results are wanted for wet weight basis.

Equation (37) was used to predict the compressive characteristics of average U.S.A. waste using compositions as estimated by the EPA (Table 11) and the particle size data for raw waste (see Appendix H). The equation is then reduced to

$$Y = -310.1 + 615.3 \log(x_1+6) - \frac{9565}{x_1+80} \qquad (41)$$

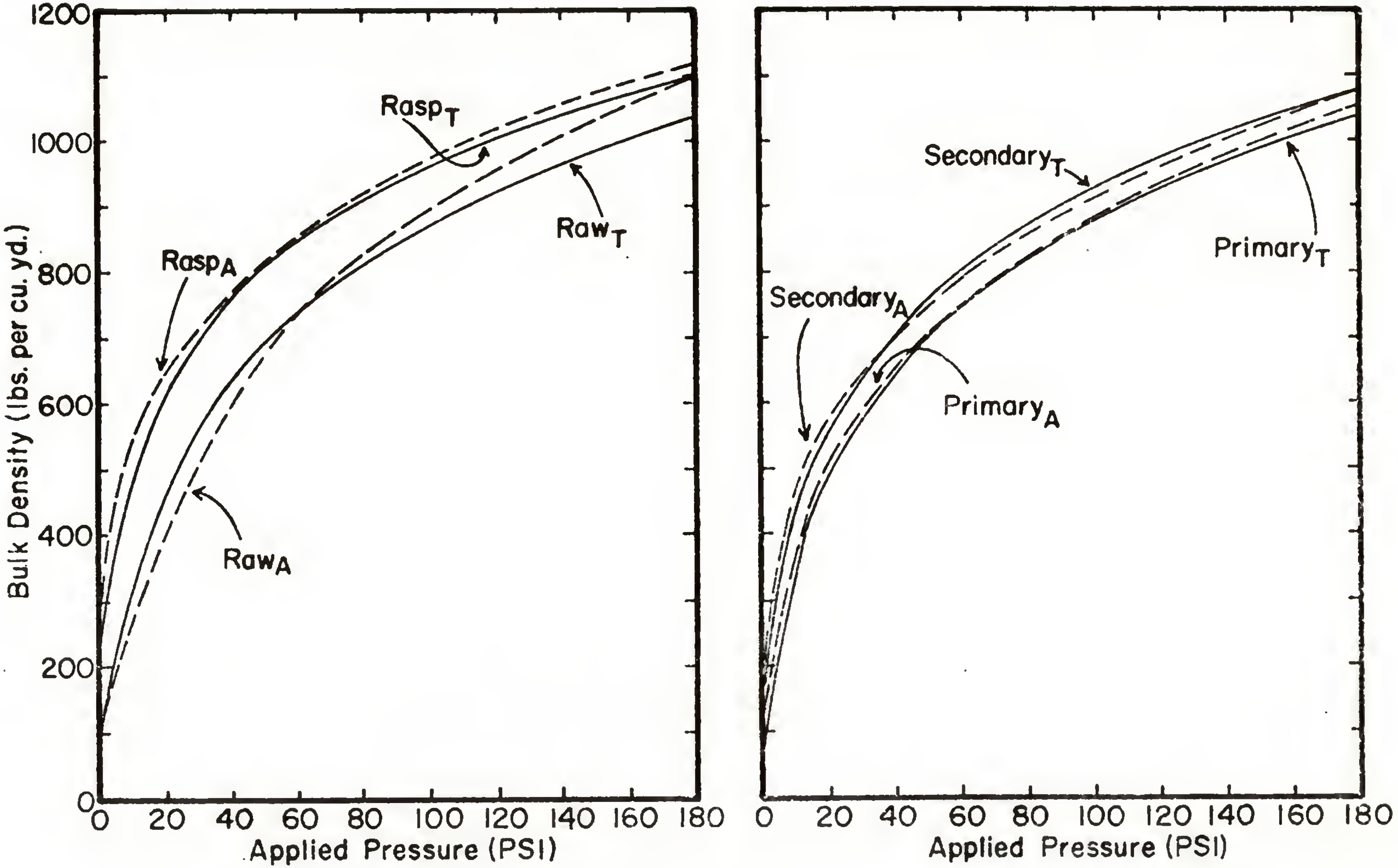


Figure 53. Comparison of compression mathematical models to the empirical curves.

where Y and x_1 were previously defined.

Similarly, the rebound equation (equation (39)) was solved for average U.S.A. waste and its equation is

$$Y = 181.3 + 95.85\ x_1^{0.35} - \frac{933.4}{\sqrt{x_1+30}} \tag{42}$$

Both of these equations can be modified for moisture content by using equation (36). The modified equations for 30 percent moisture content are:

Compression:

$$Y = -443 + 879\ \log(x_1+6) - \frac{13,664}{x_1+80} \tag{43}$$

Rebound:

$$Y = 259 + 136.9\ x_1^{0.35} - \frac{1333}{\sqrt{x_1+30}} \tag{44}$$

The models were then compared to the results in Figure 23. Equation (43) predicted results that were remarkably close to those of the APWA study [107,113] for refuse under compression. For example, the model predicted a density of 2,453 lbs. per cu. yd. at 2,000 psi pressure, while the value from the curve was 2,400. The equation also was very close to the U.S. Public Health Service and American Baler Company studies.

The results of equation (44) also were compared to the rebound curve shown in Figure 23. The model consistently over-predicted the density of the rebounded waste. For example, at 2,000 psi, the model predicted a density of 2,187 lbs. per cu. yd., while the value from the curve was only 1,500 lbs. per cu. yd. A good part of this difference is probably due to a longer period of rebound by APWA. At any rate, the equation is thought to be accurate at the lower pressures.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The knowledge of the particle size and density-compression characteristics of raw and processed refuse was surprisingly meager. No reliable quantitative methods were identified that had been developed sufficiently for measuring these parameters. In addition, the analytical results reported in the literature varied considerably because of varying refuse compositions. Previous evidence indicated that, although the refuse composition differed considerably, the physical and chemical characteristics of each component (e.g., paper, textiles, glass, metals, etc.) were reasonably uniform.

The stated objectives of this research were many-fold. First, it was intended to develop reliable analytical techniques for determining the particle size distributions of both the component and the composite wastes and the density-compression of raw and processed wastes. These techniques were to be utilized in defining the subject characteristics of various types of wastes.

Relationships were to be defined between (1) different types of refuse shredders and the particle size distributions; (2) waste components and composite; and (3) waste particle size distributions and density-compression. A methodology was to be developed to predict the particle size distribution of both raw and processed waste.

The particle size spectrum was determined by using large soil-aggregate sieves and large-sized samples (the dried samples varied from 2.17 to 16.55 lbs.). Four different types of waste were analyzed: raw refuse and three different types of shredded waste (hammermills and rasp). A total of 63 test samples were sieved and separated into 13 components. Particle size distributions were obtained for the composite wastes and their constituents.

The density and compressibility of "twin samples" of the particle size analysis were determined using a 12.094 in. ID x 10.969 in. test cylinder. Some 79 dried test samples were analyzed by the combined density-compression test. The average sample size was 3.23 lbs. The raw and shredded wastes were gently placed into the cylinder and the loose bulk density initially determined. The samples were statically loaded using a hand-pumped hydraulic cylinder with a large steel piston. Increased pressures from 0 to 174.7 psi were incrementally applied to the test samples and the corresponding compressed densities measured. The total loading time averaged 29.3 minutes. Rebound measurements were determined after applied pressures of 5, 10.2, and 174.7 psi.

The particle size analytical techniques were found to be simple, dependable, and reproducible. About two hours were required to sieve each sample; a considerably longer time period (8 hours) was required to classify each composite waste into components.

The analytical procedures were successful in eliminating the experimental errors due to variations in composition. The sieving coefficient of variation of the mean particle size for raw and shredded waste ranged from 1.25 to 2.13 percent. With the exception of raw waste, the experimental error was nearly constant at all points along the cumulative distribution curve.

The density-compression analytical techniques were found to be dependable and reproducible. The density coefficient of variation was 1.74 and 3.66 for two different types of hammermill shredded waste. The standard error of means for the compression test varied from 3.02 to 10.27 lbs. per cu. yd., depending on the applied pressure. These values also included variations in samples. The greatest variations were with high applied pressures and large-sized particle wastes.

Highly skewed and complex particle size distributions were obtained for the composite waste. Also, many of the component distributions were skewed. Common mathematical functions were fitted to each component distribution and methodologies were developed for predicting particle size distributions of different raw and processed composite wastes using these component models. The index of correlation for this fit averaged 0.94.

The distribution of the composite waste is the sum of the distributions of its components. Therefore, the composite waste distributions were affected predominantly by their major percentage components.

Hammermills tended to reduce the waste to log-normal or exponential distributions, while beta distributions predominated for the waste from the rasp mill. The rasp mill provided the most finely divided material. Successive shredding by the hammermills increased the coefficient of variation. It was reduced only slightly by the rasp mill.

The mean particle size of shredded waste was found to be directly proportional to the size of the shredder grates, as measured by the minimum width of the largest grate opening.

Each waste component reacted differently to shredding and to the different types of shredders. Glass was the easiest to reduce by hammermills, while the glass from the rasp mill was considerably coarser. Textile waste was the hardest component to reduce by the hammermills. Metals and plastics were also difficult to break down.

Certain components (sand, glass, ferrous, non-ferrous, cardboard) had very unusual distributions (either peaked or located at the extreme of the composite distribution) which made them amenable for removal or concentration by utilizing a series of sieves.

The density of refuse (both loose and compressed) varied greatly with moisture content. The dry bulk density of compressed waste was found to vary with the logarithm of applied pressures. The waste particle size distribution (as defined by the product of the mean and standard deviation) and the waste composition (light vs. heavy components) also were important variables. Mathematical functions were fitted to the data. The models were very accurate in predicting the data obtained from this study and that reported by others. The prediction equations were modified to account for moisture content.

Recommendations

Several new areas of research, related to the particle size and density-compression of raw and processed refuse, were suggested during this study. In addition, equipment and time constraints prevented other avenues from being investigated. Suggestions for future research are listed below.

Particle size analysis:

1. This research lacked the capability of defining the particle size of the very large and bulky objects. In addition, an insufficient number of screens were provided above the one-inch size. Thus, it would be desirable to add several larger screens (e.g., 3, 6, 12, 24, 36, and 48 in.) in order to reliably define the larger end of the particle size distribution.

2. Certain components (e.g., glass, metals, paper) appeared to be amenable to removal or concentration by sieves. Different types, sizes, and combinations of sieves (e.g., rotary vs. vibrating) should be evaluated.

3. The particle size distributions should be determined for other types of shredded waste.

4. The effect of grate size on the mean waste particle size was evaluated by only six observations. This relationship should be more fully refined, not only for additional shredders of the same type, but also for different types of shredders.

5. Several key parameters (hammer wear and waste moisture content) have been mentioned by other researchers as important factors in the reduction of solid waste. This relationship needs further refinement for various types of shredders.

6. The component particle size distributions of wastes from other locations should be determined to prove that they are relatively similar and the prediction equations are applicable.

Density-compressibility:

1. The compression-consolidation of refuse has been shown to vary with the duration of applied pressures. This relationship needs to be more fully explored.

2. The effect of varying moisture contents on both the compressibility and consolidation of waste should be more fully understood, especially at the higher moisture contents.

3. The compression equipment should be modified for additional studies. First, a two-way hydraulic cylinder should be obtained so that the heavy piston can be withdrawn from the cylinder without disturbing the sample. Secondly,

a properly sized pressure gage should be used so that pressures between 0 and 5 psi can be obtained. Also, it would be desirable to install a gage to determine the location of the piston more readily.

4. Larger equipment is needed, both to obtain the compressibility of wastes at higher pressures than those studied and to establish the compression characteristics of larger particle sized raw waste.

5. The density and compressibility of wastes from other locations should be determined to prove that they are relatively similar and that the prediction equations are applicable.

APPENDIX A

DESCRIPTION OF SAMPLES

A-1. Raw refuse samples collected from the Gainesville, Florida, landfill.

Sample Number	Gross Samples		Sieve Test Samples		Compression Test Samples[a]	
	Date Collected	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)
R-1	9/2/71	6059.0	1	6059.0	2	829.1, 798.6
R-2	9/30/71	4316.9	1	4316.9	2	1385.6, 1572.5
R-3	10/4/71	7504.5	1	7504.5	2	1943.1, 2035.5
R-4	10/7/71	4187.7	1	4187.7	2	924.7, 825.3
R-5	10/11/71	3103.7	1	3103.7	2	1294.8, 864.5
R-6	10/13/71	3824.6	1	3824.6	2	1113.3, 1329.5
R-7	10/15/71	3620.5	1	3620.5	2	1186.6, 1616.2
R-8	10/18/71	2137.2	1	2137.2	2	455.0, 659.3
R-9	10/21/71	5031.8	1	5031.8	2	732.5, 844.0
R-10	10/25/71	6664.7	1[b]	6664.7	4	1350.0, 1326.3 1035.2, 1435.7
Total		46450.6	10	46450.6	22	25557.3
Mean		4645.1		4645.1		1161.7

[a] Samples R-1 through R-9 were modified for the compression test.

[b] Same sample was analyzed five times for reproducibility analysis.

A-2. Primary shredded samples collected from the conveyor belt after the primary shredder at the Gainesville, Florida, compost plant.

Sample Number	Gross Samples		Sieve Test Samples		Compression Test Samples	
	Date Collected	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)
P-1	4/29/71	--	1	937.4	1	957.8
P-2	6/21/71	--	1	1498.2	1	1224.9
P-3	7/6/71	--	1	2264.2	1	1340.1
P-4	7/7/71	--	1	1555.6	1	930.0
P-5	8/9/71	--	2	981.9, 1164.0	2	920.4, 1060.6
P-6	8/10/71	--	2	848.1, 611.1	2	497.0, 485.7
P-7	8/10/71	4541.5	1	925.9	2	641.4, 772.1
P-8	8/10/71	9108.6	1	1627.5	2	1441.4, 1648.8
P-9	8/10/71	9127.5	2	1431.7, 1085.2	2	1020.2, 1343.1
P-10	8/10/71	8985.6	2	1096.0, 1119.6	2	939.7, 1285.1
P-11	8/10/71	5490.6	1[a]	945.7	2	1103.2, 1127.2
P-12	8/10/71	6155.7	1	980.1	2	996.3, 1103.0
P-13	8/10/71	6565.8	1	984.7	2	1173.1, 1060.7
P-14	8/10/71	5473.9	1	1192.8	1	1184.6
Total			18	21249.7	23	24256.4
Mean				1180.5		1054.6

[a] Same sample was analyzed five times for reproducibility analysis.

A-3. Secondary shredded samples collected from the "Tripper" after the secondary shredder at the Gainesville, Florida, compost plant.

Sample Number	Gross Samples		Sieve Test Samples		Compression Test Samples	
	Date Collected	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)
S-1	4/29/71[a]	--	1	1005.3	1	1022.3
S-2	5/20/71[b]	--	1	2231.2	1	1606.3
S-3	6/22/71[a,b]	--	1	1115.0	1	699.1
S-4	6/28/71	--	1	4000.9	2	1679.8, 2507.3
S-5	7/2/71	--	1	1792.4	1	1466.2
S-6	7/30/71	--	2	1353.0, 1163.7	4	1350.8, 1435.5 1318.5, 1387.1
S-7	8/9/71	--	2	1115.7, 1121.3	2	1150.3, 1208.4
S-8	8/10/71	11227.0	2	1612.8, 1148.8	1	2239.2
S-9	8/10/71	10953.3	1	1298.3	2	1638.8, 2240.4
S-10	8/10/71	6062.8	1	991.6	2	1355.7, 1375.2
S-11	8/10/71	7991.5	1	1272.4	2	1571.2, 1651.1
S-12	8/10/71	8892.7	1[c]	1435.2	2	1380.4, 1487.8
S-13	8/10/71	8587.8	1	1094.5	2	2045.7, 1272.9[d]
S-14	8/10/71	5652.8	1	983.1	1	1848.7
S-15	8/10/71	7319.8	2	1227.8, 1398.4	1	1699.7
Total			19	27361.4	25	38638.4
Mean				1440.1		1545.5

---

[a] Magnets removed most of the ferrous.

[b] Sludge added.

[c] Sample was analyzed five times for reproducibility analysis.

[d] Compression cylinder not full.

A-4. Rasp shredder samples collected after the rasp shredder at the Johnson City, Tennessee, compost plant.

Sample Number	Gross Samples		Sieve Test Samples		Compression Test Samples	
	Date Collected	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)	Number Analyzed	Size Dry-Wt. (gms.)
J-1	6/71	--	1	3639.0	2	2690.0, 3159.2
J-2	6/71	--	1	2112.1	2	2882.0, 2796.0
J-3	6/71	--	1	2160.7	3	3038.0, 2943.5, 3622.0
J-4	6/71	--	1	2332.7	2	2893.4, 3177.8
Total			4	10244.5	9	27201.9
Mean				2561.1		3022.4

APPENDIX B

GAINESVILLE, FLORIDA, COMPOSTING PLANT

The Gainesville composting plant was owned and operated by the Gainesville Municipal Waste Conversion Authority, a non-profit authority consisting of representatives from the City of Gainesville, Alachua County, and the University of Florida. Refuse from all three governmental units was received and processed at the facility.

The composting project was financed in part by a Demonstration Grant (No. DO-1-UI-00030) issued by the Bureau of Solid Waste Management of the U.S. Public Health Service (now the Office of Solid Waste Management Programs, U.S. Environmental Protection Agency). The author was the U.S. Public Health Service Project Officer of the Gainesville, Florida, composting plant from 1966 to 1970. He was "in-residence" at the plant from 1968 to 1970.

The composting plant was constructed in 1967 and began accepting municipal refuse in early 1968. It received refuse until August 10, 1971, when it closed due to economic and environmental problems. The plant was designed to process 150-tons of refuse in an eight-hour work shift.

Major modifications were made to the plant during mid-1969, when the original primary shredder (Centriblast Corp.) and ballistic separator failed and were replaced with a larger shredder (Williams Patent Crusher and Pulverizer Co., Inc.) and an electromagnetic separator.

Gainesville is basically a "university town" with predominantly residential areas. The few light industries in town did not produce any uniquely industrial waste. Thus the refuse composition was representative of the residential areas, normal commercial establishments and the university with a large medical center complex. There were several refuse composition studies at Gainesville [10,11,20,73]. The most extensive work was done during the week of September 10-16, 1969, when 33 samples were collected and analyzed. The results are provided in Table B-1. Six samples were collected at the compost plant every 1-1/2 hours throughout the period when the plant was operating and receiving waste (except for Saturday when only three samples were collected). The sample sizes varied from 37 to 101 pounds with a total weight of 2,026 pounds (the average sample size was 61.4 pounds).

In a separate study [11], the moisture content of the raw refuse was found to vary from 16 to 50 percent with the mean at 27.2 percent. The standard deviation of the moisture content was 3.56 percent. These results were obtained from 30 samples collected from August to October, 1969.

After the refuse was received at the plant, it was weighed, deposited at the receiving area and then transferred to the salvaging area by a conveyor system which included an oscillating conveyor. This device loosened the material and distributed it evenly on the picking belt, thus making it easier to separate the refuse and prevent surge loading on the primary shredder. Normally, paper products (cardboard, newsprint, and magazines) and scrap metal were manually removed at the picking belt and sold for salvage. Because of the depressed market for paper products, very little paper

Table B-1

Summary of Refuse Composition at Gainesville, Florida[a]

Refuse Category	Range, Percent (wet wt. basis)	Weekly Average, Percent (wet wt. basis)
Food waste	0.31 - 21.96	5.23
Garden waste	0 - 55.19	12.71
Paper products	22.69 - 91.55	49.65
Salvageable[b]	1.43 - 63.18	23.64
Cardboard	0 - 57.45	14.95
Other	0 - 26.13	8.69
Nonsalvageable	8.94 - 48.90	26.01
Plastic, Leather, Rubber	0.26 - 21.94	4.61
Textiles	0 - 7.31	1.61
Wood, Limbs, Sawdust	0 - 29.11	6.20
Miscellaneous combustibles	0 - 5.39	0.30
Metal	0.33 - 20.51	8.04
Ferrous	0.26 - 20.26	7.44
Nonferrous	0 - 2.42	0.60
Glass and Ceramic	0 - 19.12	7.06
Ash, Earth, Rock, etc.	0 - 27.60	4.59
TOTAL		100.00

[a] Information was obtained from Ref. 20.

[b] As used here, the term salvageable paper refers to those pieces of paper which appear to be large enough, dry enough, and clean enough to be separated at the sorting platform for subsequent sale.

was salvaged during the period when samples were collected from the plant. Normally, a negligible amount of scrap metals were removed.

Bulky items such as mattresses, sofas, tires, large pieces of wood, heavy metal and appliances, were also removed from the refuse at the salvaging area (prior to shredding) and taken to a land disposal site. Most of the bulky items were removed to prevent the conveyor system to the primary shredder from clogging. Some of these items also could have caused damage or excessive abrasion if allowed to enter the shredders. They also would reduce the quality of the compost if allowed to remain. About 10 percent of the incoming waste was manually removed as bulky materials.

After removing salvagable and bulky materials, the remaining refuse was transferred to the Williams primary shredder on another oscillating conveyor. After the first shredding, the refuse passed under an electromagnetic separator which removed most of the remaining ferrous metals before the refuse entered the secondary shredder (Williams Crusher and Pulverizer Co., Inc.). Raw or digested sewage sludge or tap water was combined with the processed waste by a set of mixing screws immediately following the secondary shredder. A second magnet removed additional ferrous metals and the remaining material was conveyed to the tripper, which is a mechanical device to remove the material from the conveyor and place it in the digesters. After remaining in the digester for four to six days, the refuse was removed, passed under a third magnet, given a final shredding, and bulk stored until removal from the plant grounds. The final grinders were used initially only in the plant operations. The plant equipment and process has been previously described in detail [11,20,73, 137,138,139].

Both Williams' shredders (Table B-2) were constructed and operated in a similar fashion, and each had a single horizontal rotor shaft to which the swinging hammers were connected. The primary shredder also had a flywheel. The design rates of the primary and secondary shredders were 30 and 20 tons per hour, respectively. Each shredder had a 400-horsepower electric motor which powered the rotor shaft by means of a flexible coupling.

Refuse in the shredders was crushed between the swinging hammers and the heavy steel breaker plate, as well as between the hammers and the grates. The refuse was pounded until it was small enough to pass through the grates located below the rotor shaft. The breaker plates (which were located directly ahead of the grates and on one side of the shredders) were periodically adjusted so the swinging hammers almost touched them. These adjustments tended to improve the efficiency of the shredders in reducing the particle sizes.

Both shredders were provided with box-type double gage bar pattern type grates. The grate openings in the primary shredder were 4-1/2 in. x 8 in. for the grate box near the breaker plate and 12 in. x 8 in. at the opposite end. The grates of the secondary shredder (during the time the samples

Table B-2

Gainesville, Florida, Shredder Specifications

Item	Primary Shredder	Secondary Shredder
Manufacturer	Williams Hammer Mill	Williams Hammer Mill
Type	K	GA
Size	460	70
Rated capacity (tons per hour)	30	20
Total shredder weight (pounds)	33,500	19,500
Rotor disc assembly weight (pounds)	14,190	9,095
Flywheel weight (pounds)	1,600	--
Rotor shaft diameter (inches)	9	9
Total rotor assembly rotational inertia (lbs.-ft.^{2})	12,237	5,727
Rotor rotational inertia (lbs.-ft.^{2})	9,305	5,727
Flywheel rotational inertia (lbs.-ft.^{2})	2,932	--
Number of hammers	30	30
Weight of hammers (pounds)	100	26 50-lb. hammers 4 16-lb. hammers

Table B-2 - Continued

Item	Primary Shredder	Secondary Shredder
Feed opening (inches)	56 x 63	24 x 70
Specified particle size after shredding (inches)	6	1
Grate opening size (inches)	8 x 4-1/2 and 12 x 8	10 x 3-1/2
Motor size (horsepower)	400	400
Motor voltage	2,400	2,400
Shaft revolutions per minute (rpm)	800	1,200
Installation date	Summer 1969	Fall 1967

were collected at the plant) were provided with 3-1/2 in. x 10 in. openings throughout, and each grate box had six openings.

The two final grinders were especially built vertical mills (Dan B. Vincent, Inc., Tampa, Florida) operated in parallel. Material fed at the top of each mill was forced between the swinging hammers and stationary screens, creating a shearing action. The screens were each three feet in diameter with 9/16-in. holes at 3/4-in. centers, providing an open area of 51 percent. Each shredder was powered by a 150-horsepower electric motor with a shaft speed of about 960 rpm. As the material became fine enough, it was forced through the 9/16-in. holes of the screens.

APPENDIX C

JOHNSON CITY, TENNESSEE, COMPOSTING PLANT

The joint U.S. Public Health Service--Tennessee Valley Authority composting project at Johnson City, Tennessee,has been described in detail elsewhere [139,140,141]. Only pertinent operations will be provided here.

The 10 ton per hour plant began operation during June, 1967, and closed during the Summer of 1971. Not all of the refuse from Johnson City was handled at the plant as commercial and industrial wastes bypassed the plant and went directly to the landfill for disposal.

Refuse was conveyed from the receiving building to the sorting station just ahead of the rasp shredder. Two or three persons removed rejects (bulky items, glass bottles, cardboard, large scrap metal, carpeting, rags, and some plastics). Most of the ferrous metals were removed at the end of the conveyor belt by a magnetic pulley. The rejects and ferrous metals amounted to approximately 25 percent of the total refuse received.

The rasp shredder (manufactured by the Dorr-Oliver Company in Holland) consisted of a circular bin, 18 ft. in diameter and 4-1/2 ft. high, in which material was moved by radial sweeps, revolving about a vertical axis at 8.3 rpm, and rasped against protruding cast steel pins on the walls and on the bottom of the chamber. The rasp, designed for 10 tons per hour, was driven by two 40-horsepower motors connected through a hydraulic coupling. The floor of this bin had perforated plates with 1-1/4 in. holes. As material became finer (from the rasping action), it dropped through these holes into the lower chamber. Thus, the rasp acted as a screen with 1-1/4 in. openings. It took about 30 minutes for the charge to build up in the rasp so that the output equaled the input. The addition of a spray of water in the upper chamber improved the shredding of cardboard and reduced dust problems.

Quantities of rags, carpeting, thread, and large pieces of wood and metal missed by the pickers accumulated in the rasp, and it was necessary to periodically shut down the machine so they could be cleaned out; otherwise, a single cleaning at the end of the day was sufficient.

A small hammermill primary shredder was also provided at the plant, but since the samples analyzed in this research were not shredded by it, there is no need to describe this machine. A device was provided to shuttle refuse into either shredder.

Sludge was added to the shredded refuse prior to the material being trucked to the windrows. A Cobey windrow turner was provided at the site, not only to aerate and mix the material, but also to provide some shredding action.

APPENDIX D

EQUIPMENT

I. Ovens

A. National Appliance Company, Napco Model 430 (Portland, Oregon)--gravity convection oven, 200°C upper range, 2,800 watts, 230 volts, 200 lbs. shipping weight, 9.3 sq. ft. shelf capacity, 2 perforated metal shelves, 2 doors, double-walled, glass wool insulated, air port at bottom, sliding exhaust shutter at top, temperature uniformity of 2°C or better throughout the temperature range, Sargent-Welch Scientific Co. catalog No. S-64127-10C, list price $630.00. (This oven was vented to an exhaust hood, thus providing a direct exhaust to the outside. When the samples were especially wet, the exhaust hood fan was operated to aid the venting.)

B. Precision Thelco Co., Model 4--gravity convection oven, temperature range to 60°C, 110 volts, 3 perforated metal shelves, small sliding exhaust shutter at top. (The bottom metal partition of this oven was removed, thus increasing its upper range temperature to above 75°C.)

II. Balances

A. Ohaus Scale Corp. (Florham Park, N.J.)--large capacity metric balance, 20 kg. capacity, sliding counterpoising tare weight (2,270 gm. tare capacity), 11 in. diameter plate, 33-1/2 in. length x 10-1/4 in. height x 11-1/4 in. width, 36 lbs. net weight, 1 gm. sensitivity (can estimate to 0.1 gm.). Sargent-Welch Scientific Co. catalog No. S-3365, list price $149.50. (This scale was used for all of the screening and composition samples over 300 gms.)

B. Torsion Balance Co., Style DLT5 (Clifton, N.J.)--medium capacity metric balance, 500 gm. capacity, 0.1 gm. sensitivity (can estimate to 0.01 gm.). (This scale was used for all composition samples from 0 to 300 gms. and all subsamples over 5 gm.)

C. Eimer and Amend Co. (New York, N.Y.)--chain balance, sensitivity 0.0001 gm. (This scale was used for all subsamples under 5 gms.)

III. Mechanical Screens

A. Gilson Mechanical Testing Screen, Model TS-2 (Malinta, Ohio)--purchased from Soil Test, Inc., Model No. CL-325, Evanston, Ill., list price $615.00. Price included machine, dust pan and five screens. Machine was a hand-clamping model, 1/3 horsepower motor, 110 volts, 60 cycle, shipping weight 485 lbs., 33 in. height x 23 in. width x 31 in. long; held up to six screens and dust pan at one time; trays were stacked 4 in. apart, thus allowing visual observation of the operation; each screen tray independently removable; trays agitated up and down, essentially a 7/16 in. vertical vibration at 10 cycles per second; machine was designed for crushed stone, gravel, slag, coal or ores, accommodating these materials up to 1 cu. ft. of sample; designed primarily for materials in the No. 4 to 4-in. coarse range.

B. Screen Trays (Gilson)--$36 to $40 each, cloth area 324 sq. in., trays were each 14-1/2 in. wide x 22-3/4 in.

long and 2-5/8 in. deep, all trays were balanced to the same tare weight, screen wire was held under tension; all Gilson screens were of U.S. Standard and Coarse Series and met the standards of ASTM, AASHO, and ACI. The screen sizes used during the research are listed in Table D-1.

C. Tray Rack (Gilson)--$36, held 7 trays.

D. Timer with bell, $10.

Table D-1

Gilson Screen Sizes

Size	Clear Square Openings		Wire Diameter	
	(in.)	(mm)	(in.)	(mm)
A. Coarse Sieve Series				
4 in.	4	101.6	0.248	6.30
2 in.	2	50.8	0.1988	5.05
1 in.	1	25.4	0.1496	3.80
3/4 in.	0.75	19.0	0.1299	3.30
1/2 in.	0.50	12.7	0.1051	2.67
3/8 in.	0.375	9.51	0.0894	2.27
B. U.S. Standard Sieve Series				
No. 4	0.187	4.76	0.0606	1.54
No. 8	0.0937	2.38	0.0394	1.00
No. 16	0.0469	1.19	0.0256	0.650
No. 30	0.0234	0.595	0.0154	0.390

IV. Compression Equipment

A. Press, laboratory model from Enerpac (Butler, Wisconsin), distributed by Hydraulic Supply Co., Orlando, Fla.

Serial No.	Item	Price
RC 1010	Single acting hydraulic cylinder (10 ton capacity, 10-1/4 in. stroke, 10,000 psi maximum pressure)	$ 61.25
P 34	Hydraulic hand pump (single speed, 10,000 psi maximum pressure)	39.60
HC913	High pressure hose (10,000 psi maximum pressure)	20.35
GF10S	Hydraulic pressure gage with auto damper (0-24,000 lbs. at 200 lbs. per division). This reading represents applied pressure to the steel piston.	53.85
GA2	Gage adaptor	7.80
HF100	Hydraulic oil	1.95
A258	Hydraulic bench press (0-10 ton capacity)	113.00
A13	Threaded adaptor saddle	6.44

B. Miscellaneous equipment constructed by technicians from the Mechanical Engineering Department, University of Florida.

1. Steel cylinder--12.094 in. ID x 11 in. height, 0.365 in. wall thickness; inside wall of cylinder was made smooth by lathe and sanding; cross-sectional area of cylinder - 114.876 sq. in.

2. Steel piston--11.843 in. diameter x 2.454 in. thick. Top of piston was bored and threaded at the center so it fit the "Threaded Adaptor Saddle." The piston weighed about 70 lbs.

3. Steel cylinder plate--11-13/16 in. diameter x 1/2 in. thick.

4. Steel hydraulic bench press plate--14-1/2 in. x 14-1/2 in. x 1 in. thick.

5. Aluminum filler plates (1/4 in. thick) were used under the cylinder.

C. Vernier Caliper from Sears Craftsman, 7 in. length, 0.001 in. graduations, inside and outside jaws, depth gage, automatic thumb lock.

D. Sears Craftsman Silicon Spray.

APPENDIX E

SIEVE AND CLASSIFICATION TEST DATA FORMS

Sample Number: 29 (P-11)
Date of Test: 9/11/71
Name of Testers: Ruf & Sloan

Weights:
Test Sample: 924.6 gms.
Sum of Fractions: 943.0 gms.
Difference: 18.4 gms.
Error: 1.99 %

Category	Weight of Material per Sieve Fraction Size (grams)												Total Category Weight (gms.)
	(1) Pan	(2) #30-#16	(3) #16-#8	(4) #8-#4	(5) #4-3/8"	(6) 3/8-1/2"	(7) 1/2-3/4"	(8) 3/4-1"	(9) 1-2"	(10) 2-4"	(11) 4-8"	(12) 8-16"	
(1) Food		0.3	1.2	1.9	2.4	2.5	2.8	2.6					13.7
(2) Garden	1.4	1.2	1.0	0.5	0.2		0.1						4.4
(3) Cardboard			1.4	0.5	3.9	2.8	7.1	4.7	46.7	129.3			196.4
(4) Paper	5.4	4.6	7.3	19.6	42.8	23.5	49.3	41.8	92.4	83.3			370.0
(5) Plastic, leather & rubber		0.2	0.6	1.1	1.3	1.0	3.7	5.4	19.9	41.9	17.4		92.5
(6) Textiles					0.3	0.6	3.8	0.1	2.9				7.7
(7) Wood & limbs		0.5	1.3	1.1	0.5		5.9		39.7				49.0
(8) Ferrous metal										104.8			104.8

(9) Non-ferrous metal					0.2	0.2		0.2						0.6
(10) Glass & ceramics		21.6	6.1	14.0	20.3	18.3	1.1		0.1					81.5
(11) Rock & gravel					1.8	1.1	4.6							7.5
(12) Ash, earth & sand		14.4	1.9	1.3										17.6
(13) Miscellaneous														0
Total Weight	Σ Categories	42.8	14.8	28.1	47.0	71.0	36.1	72.9	54.7	201.6	359.3	17.4	0	945.7
	Initial	42.4	14.8	28.1	47.0	71.0	36.0	72.4	54.3	201.4	358.3	17.3	0	943.0
Size of sub-sample (grams)		Estimate of 2 fractions	0.1447	1.1460	5.605	44.9								

APPENDIX F

REFUSE CLASSIFICATION SCHEME

1. Food--Sometimes called garbage. Consists largely of putrescible organic matter. The animal and vegetable waste resulting from the handling, preparation, cooking and serving of food. Examples are bread, orange peels, nut shells, bones, feathers, etc.

2. Garden--The wastes from gardens and yards. Examples are leaves, grass clippings, pine needles, shrub trimmings, weeds, and twigs less than 1/4 in. in diameter. This category does not include limbs and branches which are 1/4 in. or greater in diameter.

3. Cardboard--Corrugated and paper products which are greater than 0.035 in. thick for a single sheet. Examples are corrugated boxes, egg cartons, shoe boxes, milk cartons, etc.

4. Other paper--Paper products which are less than 0.035 in. thick for a single sheet. Does not include cardboard. Examples are newspapers, magazines, wrapping paper, bags, etc.

5. Plastic, leather and rubber--The waste of materials constructed from plastic, leather and rubber. Examples may include milk cartons, liquid soap containers, shoes, tires, cellophane, plastic bags, styrofoam, toys, etc.

6. Textiles--Cellulosic protein and woven synthetics. Examples are clothes, curtains, towels, bedding, rags, rugs, etc.

7. Wood and limbs--Wood construction material and limbs and branches greater than 1/4 in. in diameter. This category

does not include twigs less than 1/4 in. in diameter. Examples are lumber, paneling, wooden boxes, furniture, logs, limbs, branches, etc.

8. Ferrous metal--Metals which are attracted to a magnet. Examples are steel cans, bottle caps, furniture, etc.

9. Non-ferrous metal--Metals which are not attracted to magnets. Examples are aluminum cans, foil, aluminum furniture, case iron, stainless steel, brass, etc.

10. Glass and ceramics--Waste constructed from glass and ceramics. Examples are bottles, dishes, crockery.

11. Rock and gravel--Rock and gravel larger than the No. 8 sieve. Examples are rock, gravel, ashes, bricks, concrete, stones, plaster, etc.

12. Ash, earth and sand--This category consists of dust, ash, earth, lint, and sand less than the No. 8 sieve. It does not include rock and gravel.

13. Miscellaneous--Materials which cannot be conveniently classified in the above twelve categories. Examples include tar shingles, dead animals, etc.

APPENDIX G

DENSITY AND COMPRESSION TEST DATA FORMS

Sample Number: 101 (P-11)
Date of Test: 9/11/71
Name of Testers: Ruf & Sloan
No. of Filler Plates Utilized: 1

Time of Test:
Final time: 3:33
Initial time: 3:08
Total time of test: 25 min.

Weight of Test Sample:
Weight of sample plus tare: 1815.5 gms.
Weight of tare: 688.3 gms.
Weight of sample: 1127.2 gms.

Notes:

Pressure Reading (pounds)	Applied Pressure, corrected (psi)	Depth Gage Reading (inches)	Method of Measuring (A,B,C)	Depth of Refuse (inches)	Bulk Density (lbs./cu. yd.)
0	0	–	–	10.469	96.4
0	0.7	3.067	B	4.948	204.0
400	4.1	4.865	B	3.150	320.4
500	5.0	2.126	C	3.061	329.7
0*	0.7	4.580	B	3.435	293.8 *
500	5.0	2.353	C	2.834	356.1
600	5.9	2.386	↓		
700	6.7	2.415			
800	7.6	2.488			
900	8.5	2.559			
1,000	9.4	2.612		2.575	392.0
--	10.0**	–		→	401.7 **
1,100	10.2	2.694		2.493	404.9
0*	0.7	2.286		2.901	347.9 *
1,100	10.2	2.732		2.455	411.1
1,200	11.1	2.810			
1,400	12.8	2.913			
1,600	14.6	2.984			
1,800	16.3	3.050		2.137	472.3
2,000	18.1	3.104			
2,400	21.5	3.209			
2,800	25.0	3.319		1.868	540.3
3,200	28.5	3.413			
3,600	32.0	3.475			

(Continued)

Pressure Reading (pounds)	Applied Pressure, corrected (psi)	Depth Gage Reading (inches)	Method of Measuring (A,B,C)	Depth of Refuse (inches)	Bulk Density (lbs./cu. yd.)
4,000	35.5	3.539	C	1.648	612.4
4,400	38.9	3.605			
4,800	42.4	3.645			
5,200	45.9	3.722			
5,600	49.4	3.755		1.432	704.8
--	50.0**	—		—	708.3 **
6,000	52.9	3.795		1.392	725.1
6,400	56.3	3.840			
6,800	59.8	3.865			
7,200	63.3	3.896			
7,600	66.8	3.921			
8,000	70.3	3.931			
8,400	73.7	3.963		1.224	824.6
--	75.0**	—		—	831.8 **
8,800	77.2	3.991		1.196	843.9
9,200	80.7	4.017			
9,600	84.2	4.036			
10,000	87.7	4.045			
10,500	92.0	4.072			
11,000	96.4	4.091		1.096	920.9
--	100.0**	—		—	923.7 **
11,500	100.7	4.095		1.092	924.3
12,000	105.1	4.115			
13,000	113.8	4.133			
14,000	122.5	4.165		1.022	987.6
--	125.0**	—		—	996.2 **
15,000	131.2	4.195		0.992	1017.5
16,000	139.9	4.223			
17,000	148.6	4.233		0.954	1058.0
--	150.0**	—		—	1061.8 **
18,000	157.3	4.254		0.933	1081.8

(Continued)

Pressure Reading (pounds)	Applied Pressure, corrected (psi)	Depth Gage Reading (inches)	Method of Measuring (A,B,C)	Depth of Refuse (inches)	Bulk Density (lbs./cu. yd.)
19,000	166.0	4.267	C		
20,000	174.7	4.257	↓	0.930	1085.3
400*	4.1	4.110	↓	1.077	937.2 *
0*	0.7	3.854	↓	1.333	757.2 *

*Rebound readings.
**Interpolations.

APPENDIX H

PARTICLE SIZE STATISTICAL DATA

Table H-1

Raw Waste Particle Size Statistical Data

Component	Arithmetic Mean (in.)	Median (in.)	Geometric Mean (in.)	Arithmetic Standard Deviation (in.)	Geometric Standard Deviation (in.)	Skewness Coefficient	Kurtosis Coefficient	Weighted Coefficient of Variation	Range of Measurable Particles (in.)	Component Composition (%)
(1) Food	2.3115	0.5553	0.6915	3.3468	1.7280	1.79	5.34	1.41	0-16	6.1352
(2) Garden	1.7430	0.4160	0.4509	2.7591	1.7813	2.09	7.11	1.93	0-16	1.6776
(3) Cardboard	10.4876	11.0259	9.5990	3.1529	0.5130	-1.74	4.34	1.31	0.05-16	8.5151
(4) Paper	5.9096	5.5541	5.2106	2.8084	0.5495	0.89	3.59	0.60	0-16	50.6935
(5) Plastic	5.3023	4.7227	4.4613	2.9655	0.6418	0.98	3.55	0.80	0.02-16	5.4439
(6) Textile	4.0353	3.7597	3.2981	2.1462	0.7262	0.27	3.03	1.73	0.02-16	2.2619
(7) Wood	3.2557	2.3099	2.3703	2.1942	0.9070	0.28	1.37	2.52	0.02-8	1.5340
(8) Ferrous	4.0662	3.5740	3.7509	1.5490	0.4335	0.42	2.11	0.97	0.02-8	13.1715
(9) Nonferrous	2.8639	2.7919	2.4693	1.4614	0.6164	2.04	13.41	1.21	0.02-8	0.8773
(10) Glass	2.7404	2.8423	2.4701	0.6849	0.6973	-2.55	8.35	1.13	0-4	8.5574
(11) Sand & rock	0.6072	0.0608	0.0797	1.3751	2.0558	3.20	12.58	1.62	0-8	1.1235
(12) Miscellaneous	0.2813	0.2813	0.2813	0	0	0	0	2.77	0.19-0.38	0.0092
Composite	5.2918	4.5984	3.8417	3.3340	1.0701	0.78	2.96	0.44	0-16	100.00

Table H-2

Primary Waste Particle Size Statistical Data

Component	Arithmetic Mean (in.)	Median (in.)	Geometric Mean (in.)	Arithmetic Standard Deviation (in.)	Geometric Standard Deviation (in.)	Skewness Coefficient	Kurtosis Coefficient	Weighted Coefficient of Variation	Range of Measurable Particles (in.)	Component Composition (%)
(1) Food	0.4833	0.3994	0.3445	0.3636	0.9079	1.08	3.90	1.01	0.02-2	1.8491
(2) Garden	0.2292	0.0883	0.1116	0.3402	1.1796	3.44	19.42	1.24	0-4	1.9180
(3) Cardboard	3.2137	2.9289	2.6068	1.7550	0.7624	0.44	2.22	0.85	0.02-8	23.3458
(4) Paper	1.8942	1.0712	1.0042	2.2115	1.2541	2.48	10.64	0.56	0-16	38.1017
(5) Plastic	2.2795	2.1680	1.6984	1.4534	0.9031	0.74	3.63	1.11	0.02-8	4.8380
(6) Textile	3.7696	3.8188	2.8213	2.2700	0.8674	-0.17	1.25	2.11	0.09-8	1.8262
(7) Wood	1.0204	0.7154	0.6713	0.8681	1.0066	1.13	3.38	1.86	0.02-4	2.3794
(8) Ferrous	2.7085	2.8043	2.5426	0.6801	0.4412	-2.10	6.01	0.85	0-4	9.3520
(9) Non-ferrous	2.3307	2.4145	2.0401	0.9173	0.6062	-0.85	2.16	1.56	0.02-4	1.0956
(10) Glass	0.1618	0.1064	0.0944	0.1547	1.1594	1.74	11.91	0.59	0-1	9.6156
(11) Sand & rock	0.1465	0.0287	0.0464	0.2448	1.5159	2.97	13.97	1.58	0-2	5.3248
(12) Miscellaneous	2.6875	2.8803	1.9558	0.9040	1.2571	-2.55	7.51	3.57	0.02-4	0.3538
Composite	2.0004	1.4558	0.9100	1.9886	1.6172	1.63	7.22	0.35	0-16	100.00

Table H-3

Secondary Waste Particle Size Statistical Data

Component	Arithmetic Mean (in.)	Median (in.)	Geometric Mean (in.)	Arithmetic Standard Deviation (in.)	Geometric Standard Deviation (in.)	Skewness Coefficient	Kurtosis Coefficient	Weighted Coefficient of Variation	Range of Measurable Particles (in.)	Component Composition (%)
(1) Food	0.5231	0.3867	0.3370	0.5067	1.0097	2.28	10.14	1.10	0.02-4	1.5327
(2) Garden	0.1987	0.0866	0.0957	0.3802	1.1631	8.00	104.21	1.45	0-4	4.4327
(3) Cardboard	1.3654	1.1309	1.0046	1.0072	0.8679	1.51	6.68	0.88	0.02-8	12.8279
(4) Paper	0.5162	0.3505	0.3258	0.5468	1.0518	3.31	22.10	0.48	0-8	39.5521
(5) Plastic	1.8986	1.0815	1.1193	1.8992	1.0958	1.28	3.33	0.93	0.02-8	4.0920
(6) Textile	1.7013	1.3661	1.3687	1.1971	0.6707	1.77	6.73	1.38	0.05-8	3.7618
(7) Wood	0.4797	0.3675	0.3436	0.4583	0.8410	3.23	17.02	1.46	0.02-4	2.3531
(8) Ferrous	1.6265	1.4897	1.3940	0.8030	0.6259	0.55	2.59	1.38	0-4	9.7693
(9) Nonferrous	1.1922	1.1803	1.0110	0.5877	0.6512	0.54	4.33	1.23	0.05-4	1.4043
(10) Glass	0.0791	0.0531	0.0478	0.0817	1.0490	2.03	8.46	0.45	0-0.75	13.7489
(11) Sand & rock	0.0519	0.0181	0.0236	0.0935	1.0717	3.64	18.67	0.79	0-0.75	5.9314
(12) Miscellaneous	0.7548	0.6943	0.5938	0.4478	0.7873	0.45	2.21	2.68	0.02-2	0.5937
Composite	0.7432	0.3750	0.3063	0.9372	1.5705	2.49	11.66	0.30	0-8	100.00

Table H-4

Rasp Waste Particle Size Statistical Data

Component	Arithmetic Mean (in.)	Median (in.)	Geometric Mean (in.)	Arithmetic Standard Deviation (in.)	Geometric Standard Deviation (in.)	Skewness Coefficient	Kurtosis Coefficient	Weighted Coefficient of Variation	Range of Measurable Particles (in.)	Component Composition (%)
(1) Food	0.4372	0.3457	0.3183	0.3278	0.8696	1.29	4.91	0.38	0.02-2	3.0579
(2) Garden	0.1505	0.0831	0.0885	0.1593	1.0802	2.00	8.89	0.39	0-2	2.8872
(3) Cardboard	0.5576	0.5315	0.4584	0.3273	0.6860	1.15	4.73	0.41	0.05-2	6.1006
(4) Paper	0.4415	0.4055	0.3526	0.2619	0.7832	1.13	5.58	0.16	0-2	48.2846
(5) Plastic	0.5654	0.5498	0.4958	0.2733	0.5570	1.14	5.75	0.28	0.05-2	2.8392
(6) Textile	0.6141	0.5743	0.5160	0.3462	0.6426	1.17	4.37	0.69	0.05-2	0.3840
(7) Wood	0.5730	0.5982	0.4969	0.2427	0.6245	-0.36	2.11	0.84	0.02-1	0.7607
(8) Ferrous	0.9667	0.8955	0.8385	0.3545	0.7712	0.05	3.11	1.12	0-2	0.2990
(9) Nonferrous	0.5758	0.5677	0.5147	0.2354	0.5209	-0.16	1.93	0.60	0.05-1	0.6764
(10) Glass	0.5319	0.5400	0.4385	0.2620	0.7507	0.18	3.17	0.19	0-2	30.3267
(11) Sand & rock	0.3689	0.1508	0.1180	0.4662	1.7500	1.42	3.86	0.63	0-2	4.3729
(12) Miscellaneous	0.1406	0.1406	0.1406	0.0002	0	--	--	1.73	0.09-0.19	0.0107
Composite	0.4719	0.4446	0.3562	0.2906	0.9154	0.87	4.52	0.10	0-2	100.00

APPENDIX I

FITTED PARTICLE SIZE DISTRIBUTIONS AND INDEX OF CORRELATIONS OF WASTES FROM GAINESVILLE, FLORIDA, AND JOHNSON CITY, TENNESSEE

Table I-1

Table of Common Probability Distributions [135]

Distribution of Random Variable x	Symbol	Equation	Parameters	Expected Value	Variance	Range of Random Variable
Exponential	EX(λ)	$y = \lambda \exp(-\lambda x)$	λ	$1/\lambda$	$1/\lambda^2$	$(0,\infty)$
Gamma	G(k,λ)	$y = \lambda^k x^{k-1} \exp(-\lambda x)/\Gamma(k)$	k,λ	k/λ	k/λ^2	$(0,\infty)$
Beta	BT(a,b,r,t)	$y = (x-a)^{r-1} (b-x)^{t-r-1}/B(b-a)^{t-1}$, where $B = \Gamma(r)\,\Gamma(t-r)/\Gamma(t)$	a,b,r,t	at $\frac{r}{t}(b-a)$	$(b-a)^2 \cdot \frac{r(t-r)}{t^2(t+1)}$	(a,b)
Log-Normal	LN($\bar{x}_g, s_{\ln x}$)	$y = \frac{1}{x\, s_{\ln x} \sqrt{2\pi}} \exp\left(-\frac{1}{2 s^2_{\ln x}} (\ln \frac{x}{\bar{x}_g})^2\right)$	$\bar{x}_g$, $s_{\ln x}$	$\bar{x}_g$ for $\ln x$	$s^2_{\ln x}$ for $\ln x$	$(0,\infty)$
Normal	N($\bar{x}, s^2$)	$y = \frac{1}{s\sqrt{2\pi}} \exp -\frac{(x-\bar{x})^2}{2 s^2}$	$\bar{x}, s$	$\bar{x}$	s^2	$(-\infty,\infty)$
Uniform	U(a,b)	$y = \frac{1}{a+b}$	a,b	$a + \frac{b-a}{2}$	$\frac{(b-a)^2}{12}$	(a,b)

Table I-2

Fitted Distributions to the Particle Size Data

Number (j)	Waste Type	Fitted Distributions (in.)	Range (in.)	Index of Correlation
(1)	Food			
R(1)	Raw	LN(0.6915,1.7280)	0-16	0.9147
P(1)	Primary	LN(0.3445,0.9079)	0-2	0.9046
S(1)	Secondary	LN(0.3370,1.0093)	0-4	0.9322
J(1)	Rasp	LN(0.3183,0.8696)	0-2	0.8952
(2)	Garden			
R(2)	Raw	LN(0.4509,1.7813)	0-16	0.8715
P(2)	Primary	LN(0.1116,1.1796)	0-4	0.9303
S(2)	Secondary	LN(0.0957,1.1631)	0-2	0.9824
J(2)	Rasp	LN(0.0885,1.0802)	0-2	0.9615
(3)	Cardboard			
R(3)	Raw	0.20N(3.0,4.0)+0.80N(12.3596,10.1761)	0-20	0.9829
P(3)	Primary	Truncated N(3.2137,3.0801)	0-8	0.9749
S(3)	Secondary	G(1.8377,1.3459)	0-8	0.9800
J(3)	Rasp	G(2.9031,5.2063)	0-2	0.9202
(4)	Paper			
R(4)	Raw	N(5.9096,7.8869)	0-16	0.9875
P(4)	Primary	LN(1.0042,1.2541)	0-16	0.9835
S(4)	Secondary	LN(0.3258,1.0518)	0-8	0.9656
J(4)	Rasp	BT(0,2,1.9934,9.0303)	0-2	0.9837

Table I-2 - Continued

Number (j)	Waste Type	Fitted Distributions (in.)	Range (in.)	Index of Correlation
(5)	Plastic			
R(5)	Raw	G(3.1969,0.6029)	0-16	0.9939
P(5)	Primary	0.1875G(2.9031,5.2063)+0.8125N(2.6718,1.7476)	0-8	0.9692
S(5)	Secondary	LN(1.1193,1.0958)	0-8	0.9821
J(5)	Rasp	BT(0,2,2.7870,9.8584)	0-2	0.9552
(6)	Textiles			
R(6)	Raw	BT(0,16,2.3913,9.4816)	0-16	0.9567
P(6)	Primary	LN(2.8213,0.8674)	0-16	0.7404
S(6)	Secondary	LN(1.3687,0.6707)	0-8	0.9896
J(6)	Rasp	BT(0,2,1.8743,6.1042)	0-2	0.8791
(7)	Wood			
R(7)	Raw	0.72LN(1.6901,0.7188)+0.28N(5.5,1.0096)	0-16	0.9077
P(7)	Primary	LN(0.6713,1.0066)	0-8	0.9654
S(7)	Secondary	LN(0.3436,0.8410)	0-4	0.9633
J(7)	Rasp	BT(0,2,3.6908,12.8824)	0-2	0.8858
(8)	Ferrous			
R(8)	Raw	G(6.8906,1.6946)	0-16	0.9841
P(8)	Primary	BT(0,8,10.15,29.98)	0-8	0.9836
S(8)	Secondary	G(4.1028,2.5225)	0-8	0.9650
J(8)	Rasp	0.40N(1.0,0.35)+0.60N(0.875,0.15)	0-2	0.9474

Table I-2 - Continued

Number (j)	Waste Type	Fitted Distributions (in.)	Range (in.)	Index of Correlation
(9)	Non-ferrous			
R(9)	Raw	0.08N(0.438,0.0163)+0.92N(3.00,1.00)	0-8	0.9795
P(9)	Primary	0.10N(0.438,0.01585)+0.90N(2.5410,0.4909)	0-8	0.9056
S(9)	Secondary	0.20N(0.438,0.01566)+0.80N(1.50,0.3202)	0-4	0.9758
J(9)	Rasp	N(0.5758,0.0554)	0-2	0.9103
(10)	Glass			
R(10)	Raw	N(2.7404,0.4691)	0-8	0.9399
P(10)	Primary	EX(6.30)	0-1	0.9954
S(10)	Secondary	EX(12.44)	0-0.75	0.9944
J(10)	Rasp	BT(0,2,3.0254,11.3758)	0-2	0.9247
(11)	Sand & rock			
R(11)	Raw	0.80LN(0.0418,1.7748)+0.20N(1.00,0.2283)	0-4	0.8966
P(11)	Primary	LN(0.0464,1.5159)	0-2	0.9358
S(11)	Secondary	LN(0.0236,1.0717)	0-0.75	0.9791
J(11)	Rasp	LN(0.1180,1.7500)	0-2	0.9107
(12)	Miscellaneous			
R(12)	Raw	U(0.1875,0.3750)	0.1875-0.3750	1.0000
P(12)	Primary	G(8.8382,3.2887)	0-8	0.6531
S(12)	Secondary	G(2.8412,3.7641)	0-4	0.9194
J(12)	Rasp	U(0.0937,0.1875)	0.0937-0.1875	1.0000

Table I-2 - Continued

Number (j)	Waste Type	Fitted Distributions (in.)		Range (in.)	Index of Correlation
Composite					
R	Raw	Complex	$Y_{Total} = \sum_{j=1}^{j=12} W_j Y_j$	0-20	0.9934
P	Primary	Complex		0-16	0.9908
S	Secondary	Complex		0-8	0.9909
J	Rasp	Complex		0-2	0.9830

Note: j = respective component
Y_j = equation of respective component
Y_{Total} = equation of composite waste
W_j = composition of respective component

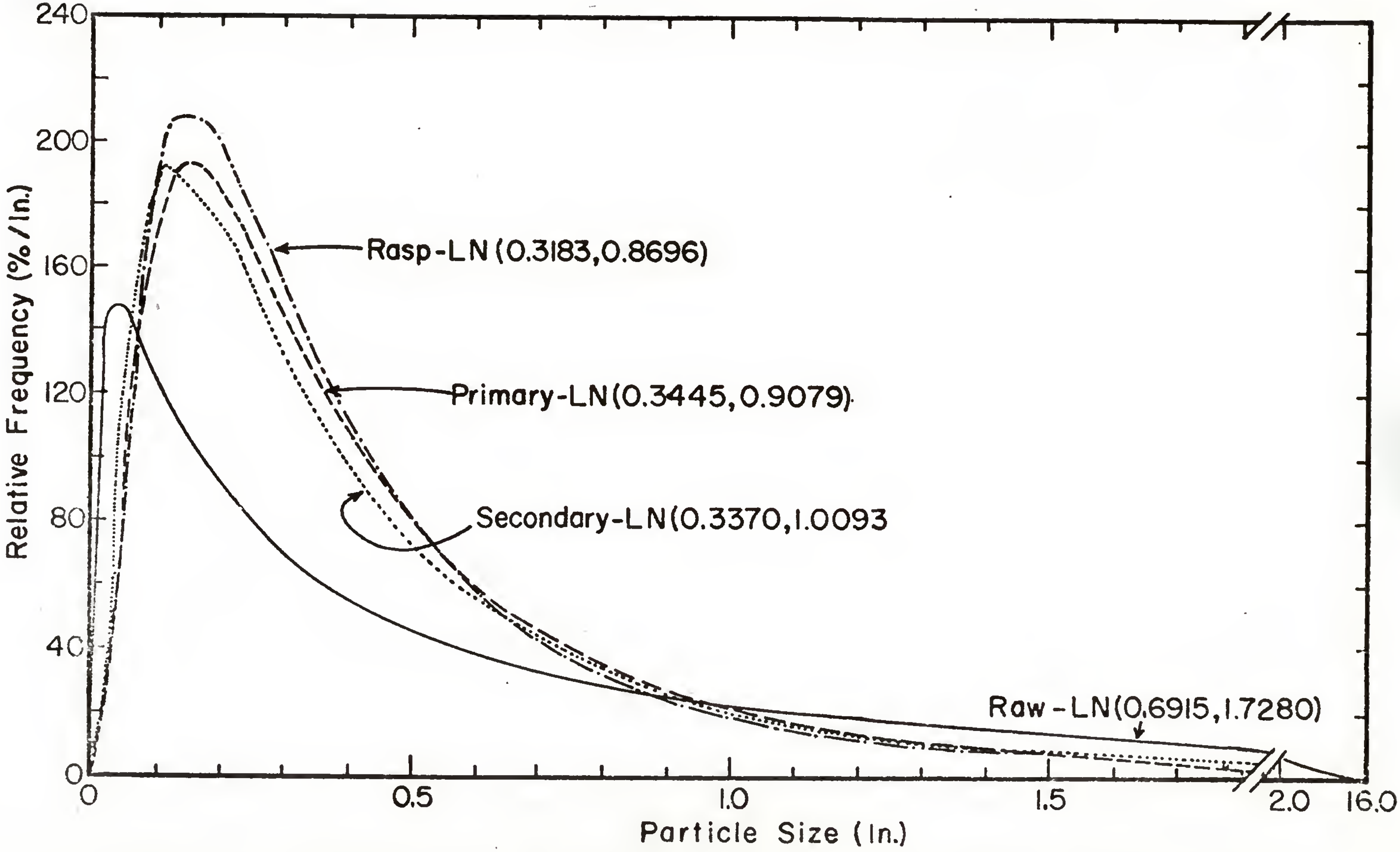


Figure I-1. Particle size distributions of food waste from Gainesville, Florida, and Johnson City, Tennessee.

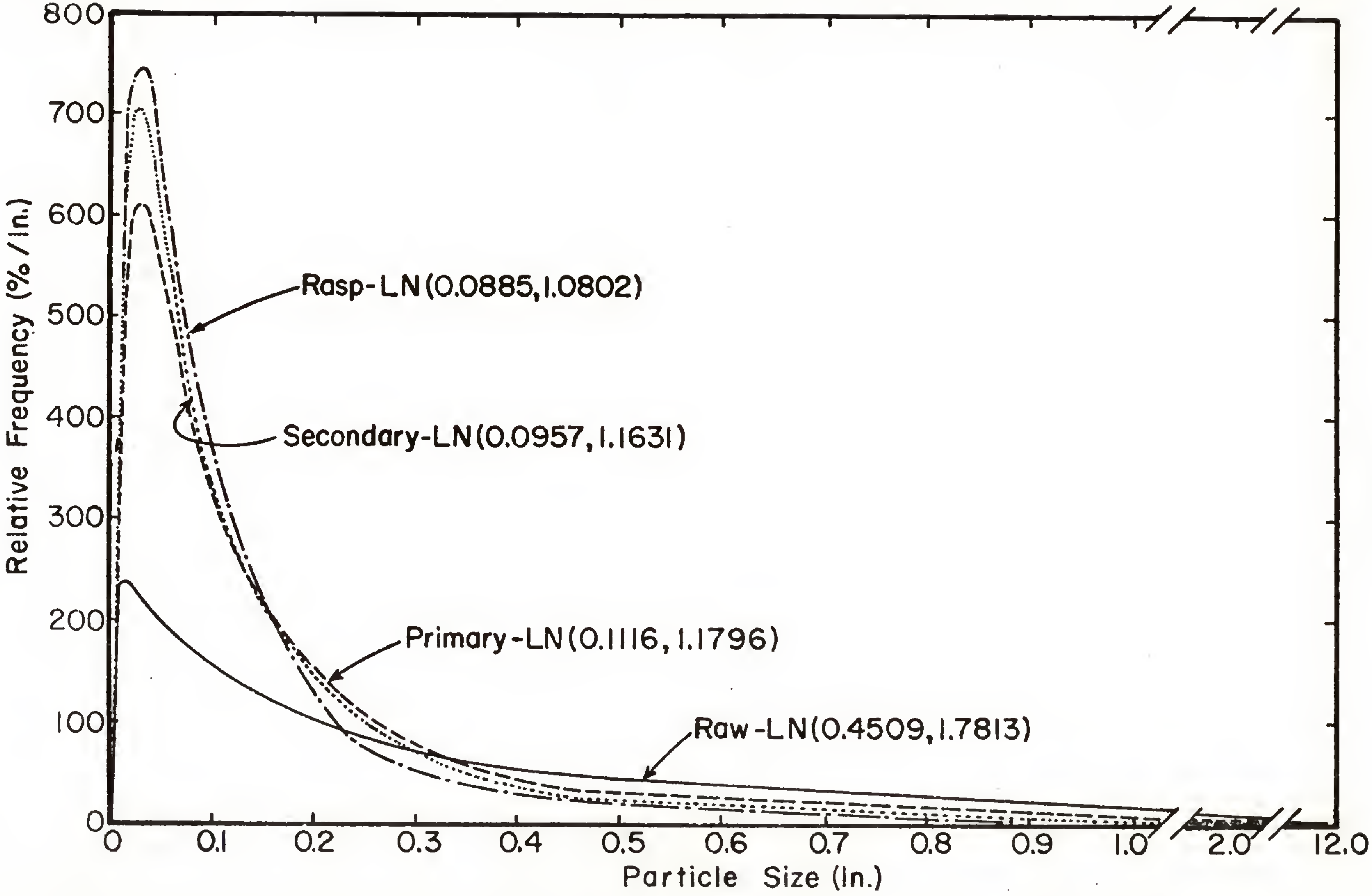


Figure I-2. Particle size distributions of garden waste from Gainesville, Florida, and Johnson City, Tennessee.

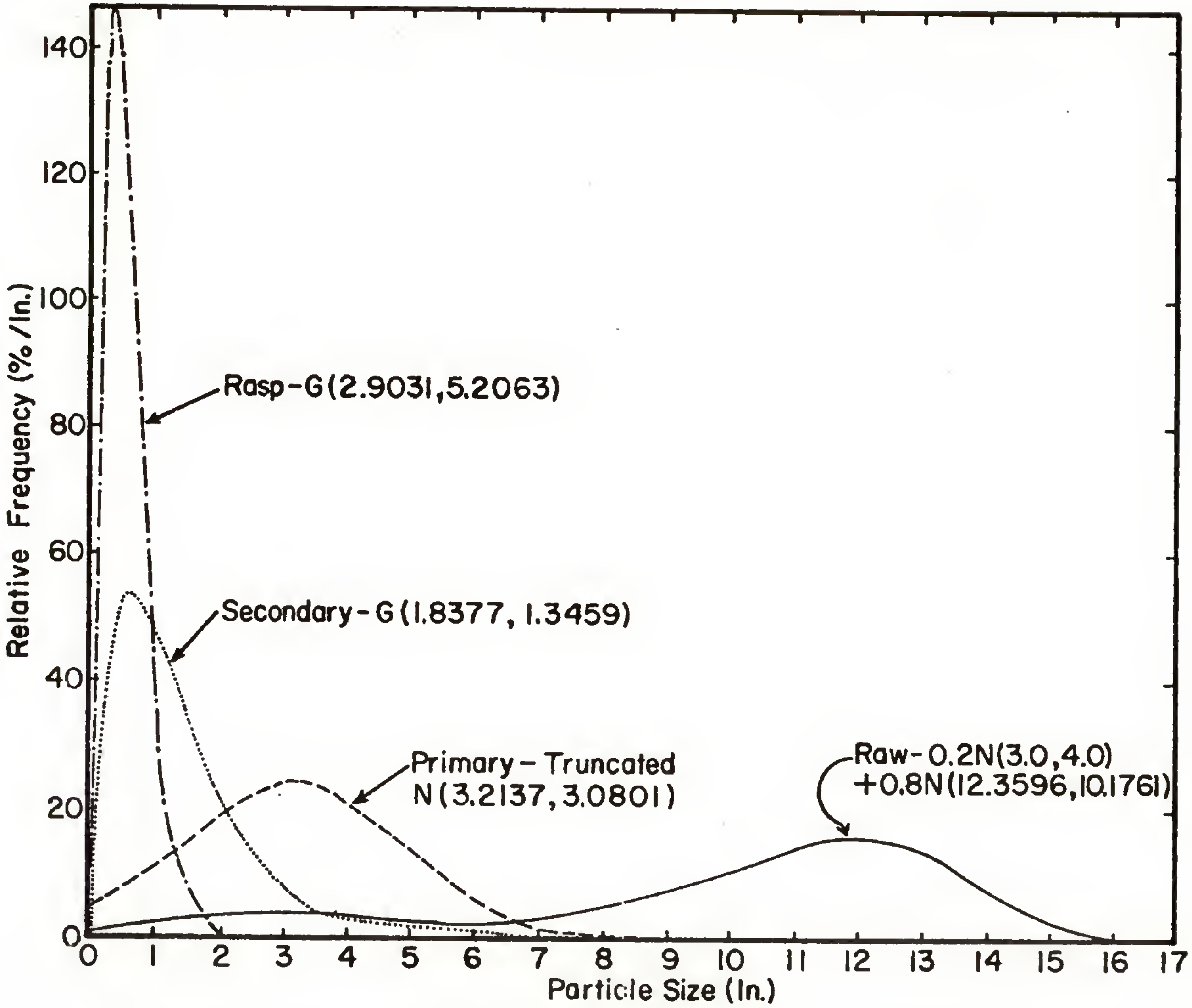


Figure I-3. Particle size distributions of cardboard waste from Gainesville, Florida, and Johnson City, Tennessee.

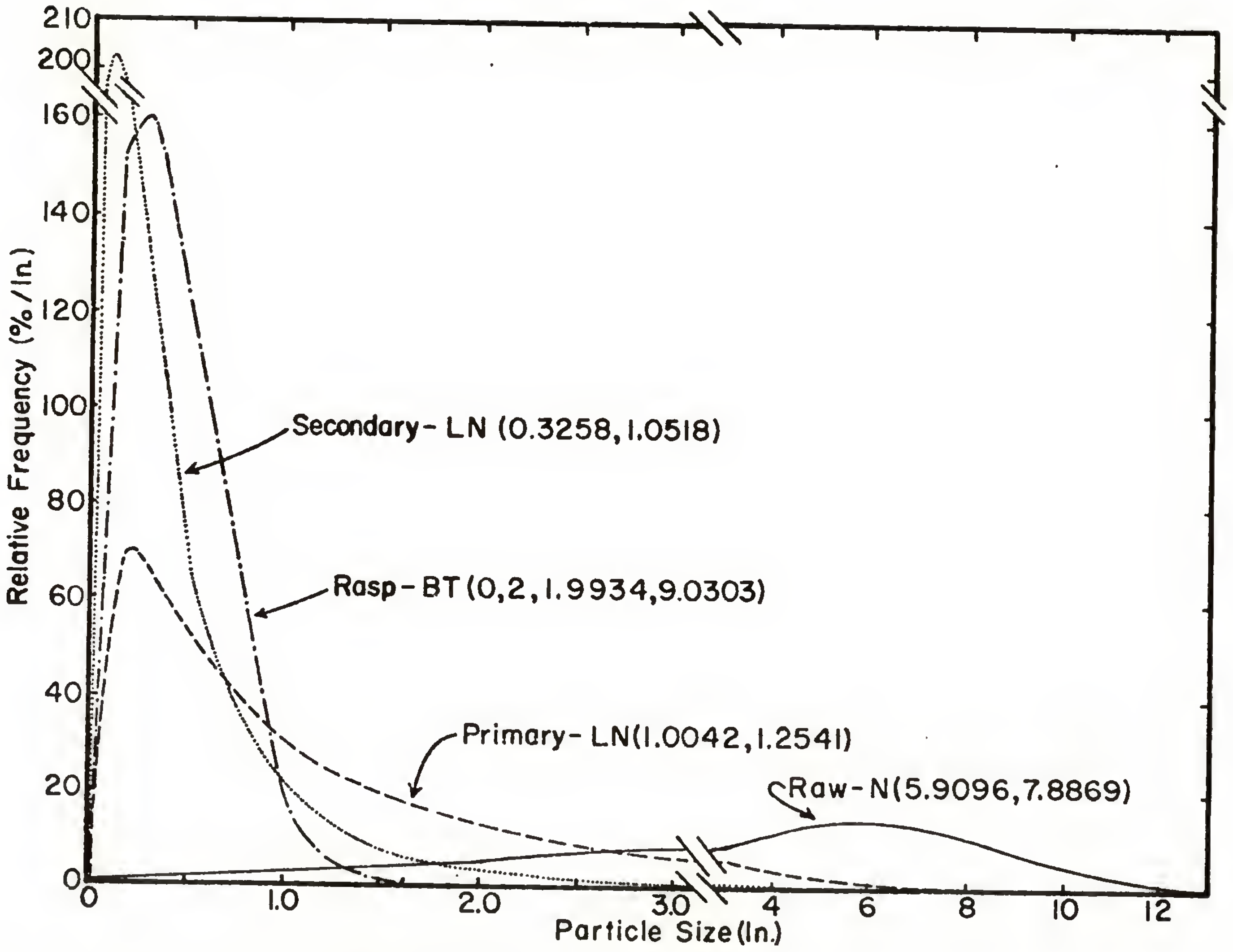


Figure I-4. Particle size distributions of paper waste from Gainesville, Florida, and Johnson City, Tennessee.

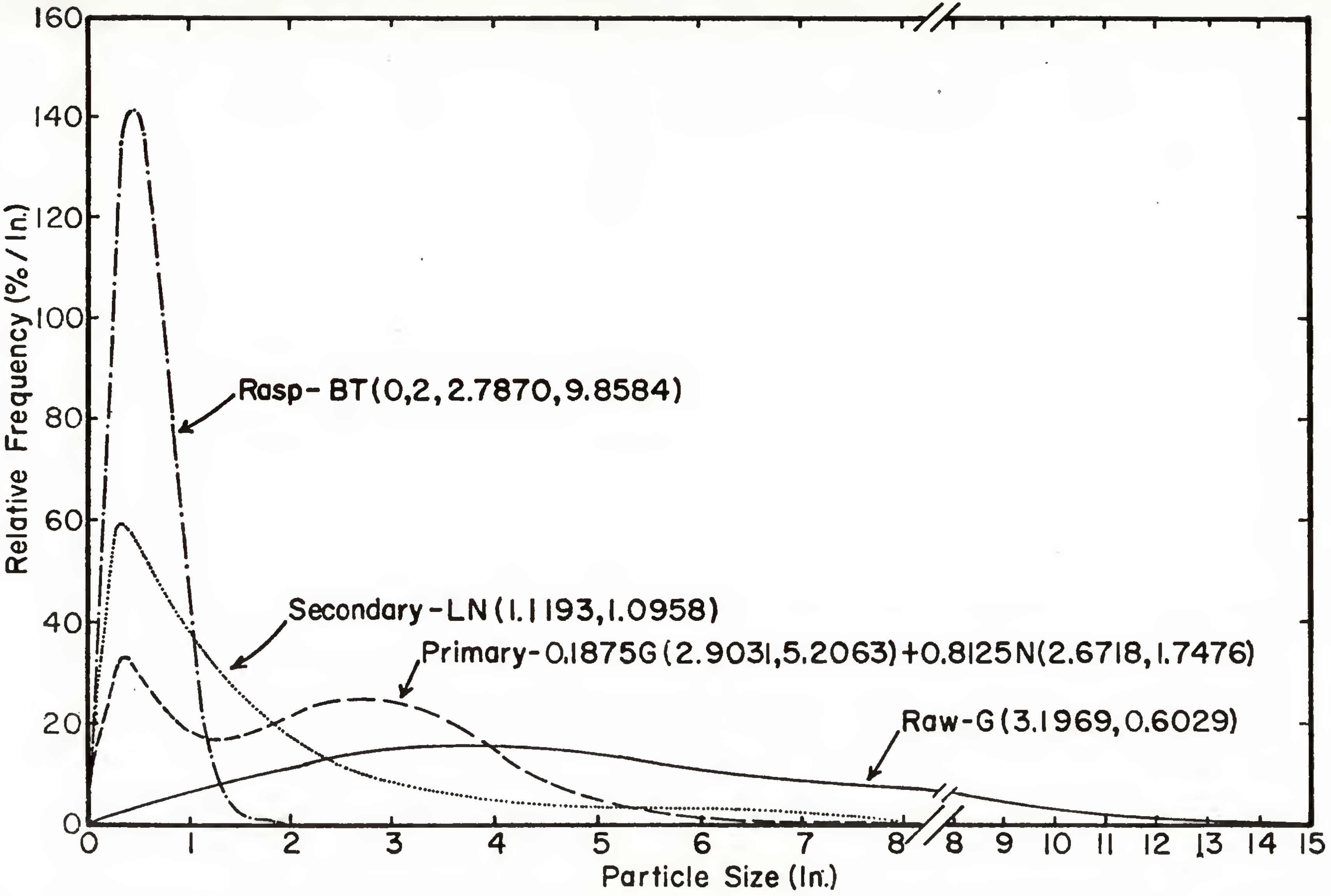


Figure I-5. Particle size distributions of plastic waste from Gainesville, Florida, and Johnson City, Tennessee.

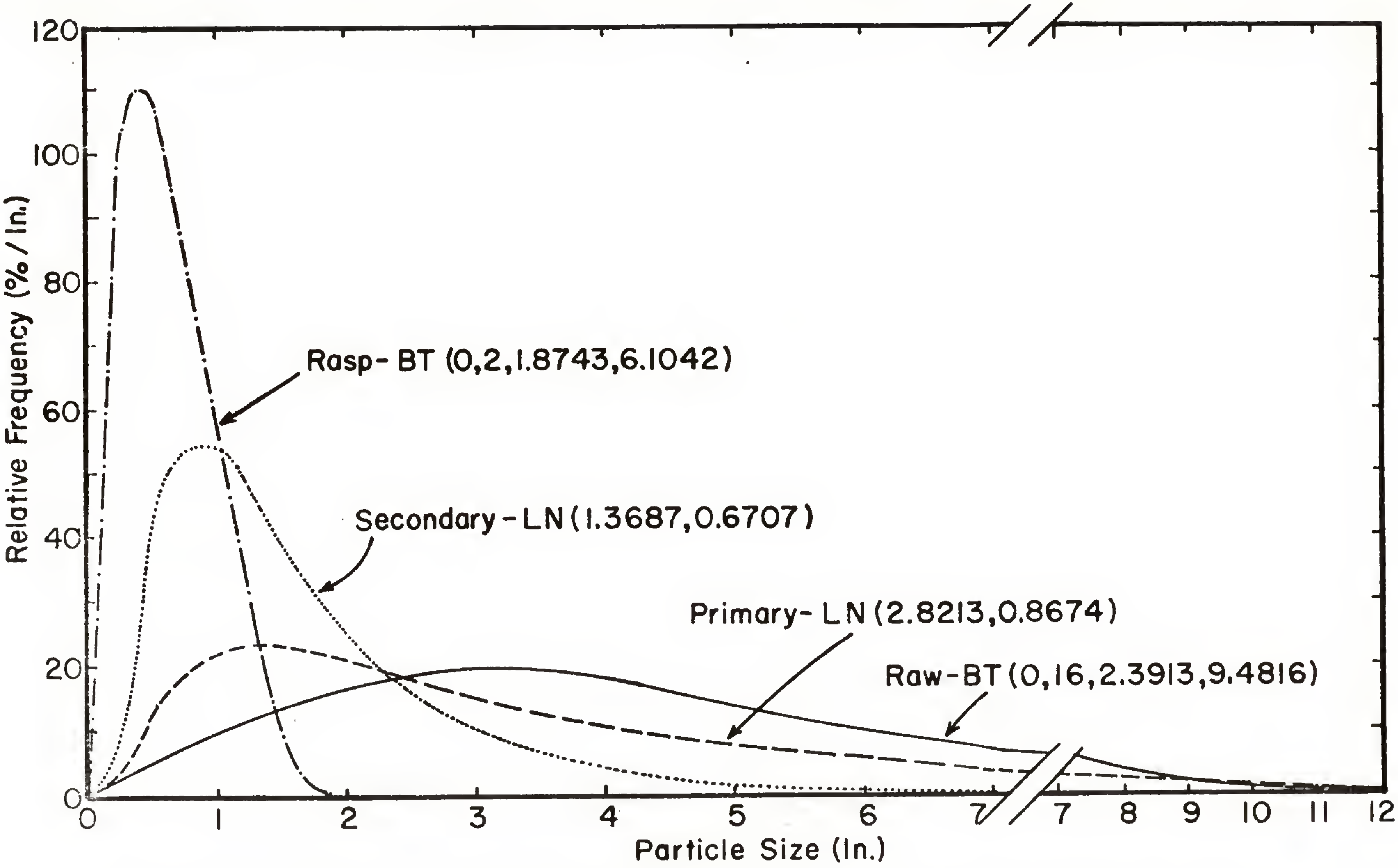


Figure I-6. Particle size distributions of textile waste from Gainesville, Florida, and Johnson City, Tennessee.

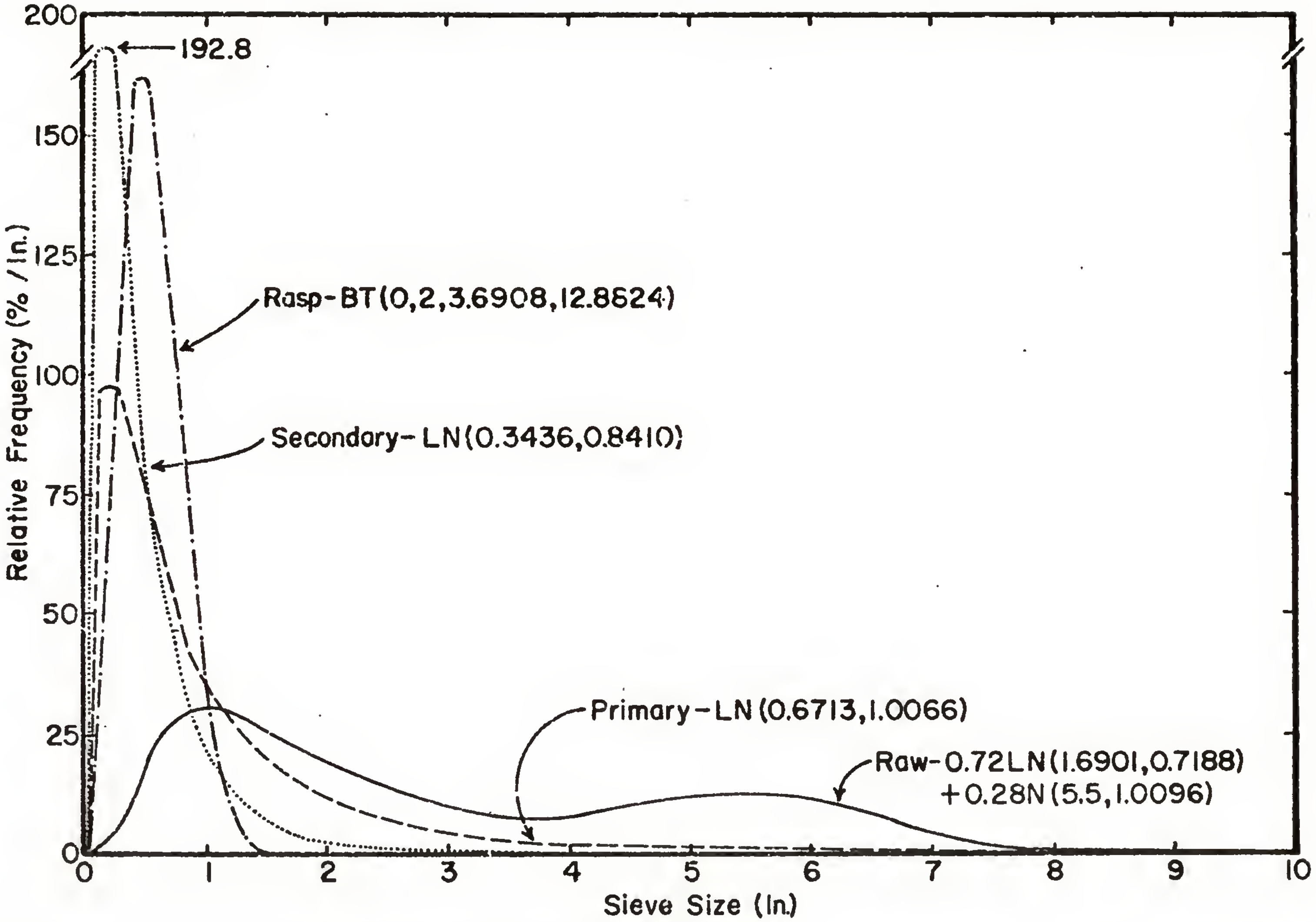


Figure I-7. Particle size distributions of wood waste from Gainesville, Florida, and Johnson City, Tennessee.

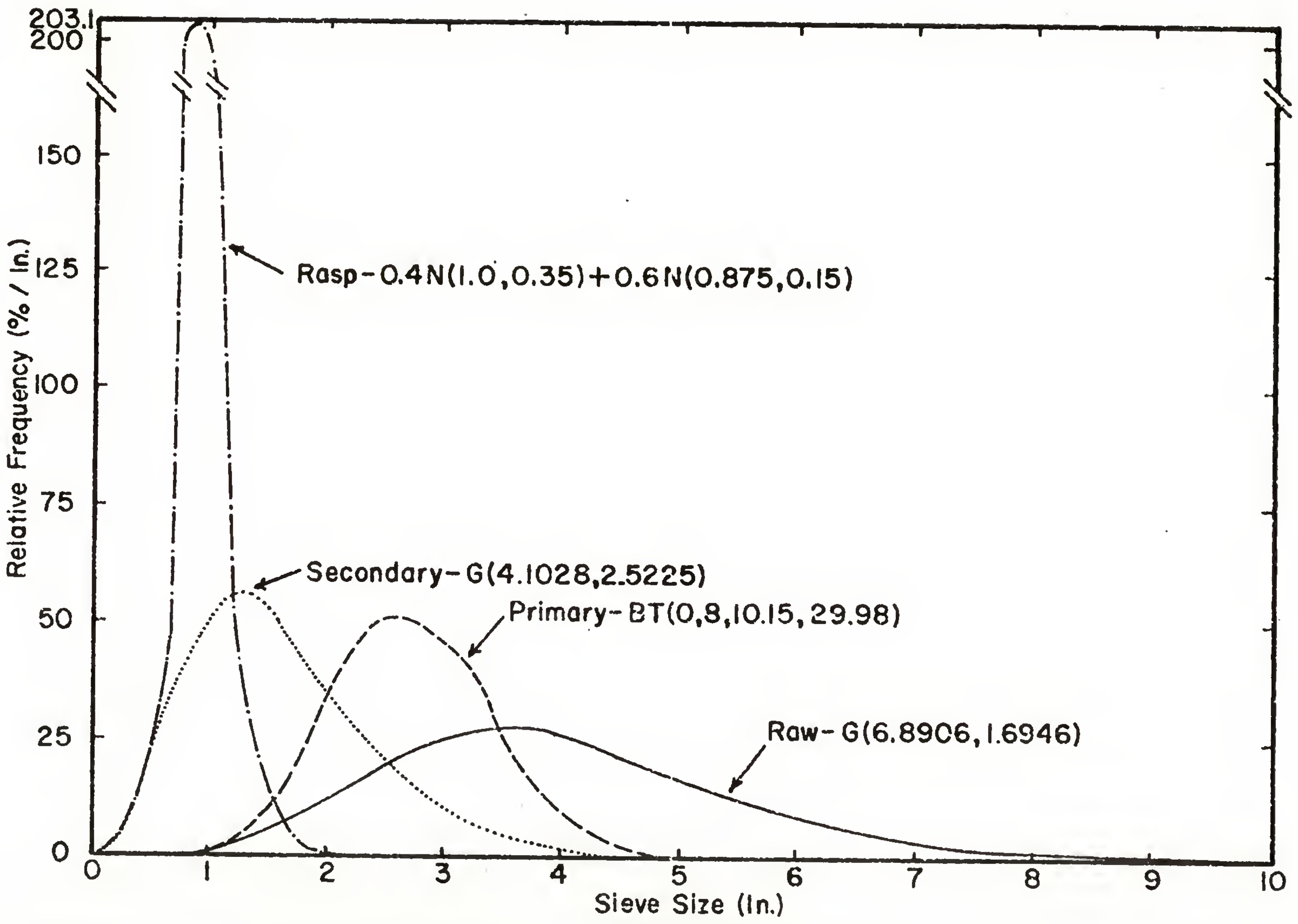


Figure I-8. Particle size distributions of ferrous waste from Gainesville, Florida, and Johnson City, Tennessee.

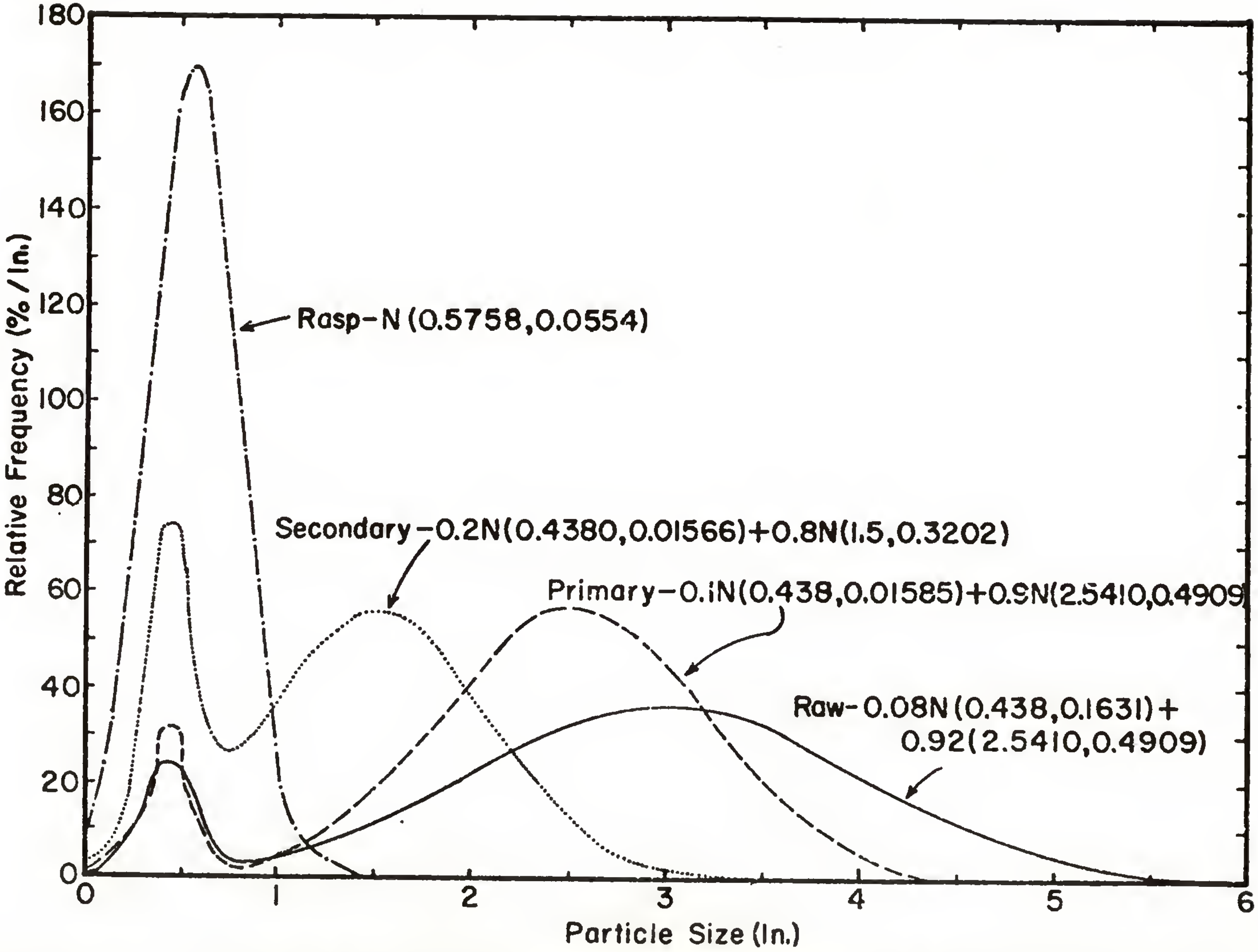


Figure I-9. Particle size distributions of non-ferrous metal waste from Gainesville, Florida, and Johnson City, Tennessee.

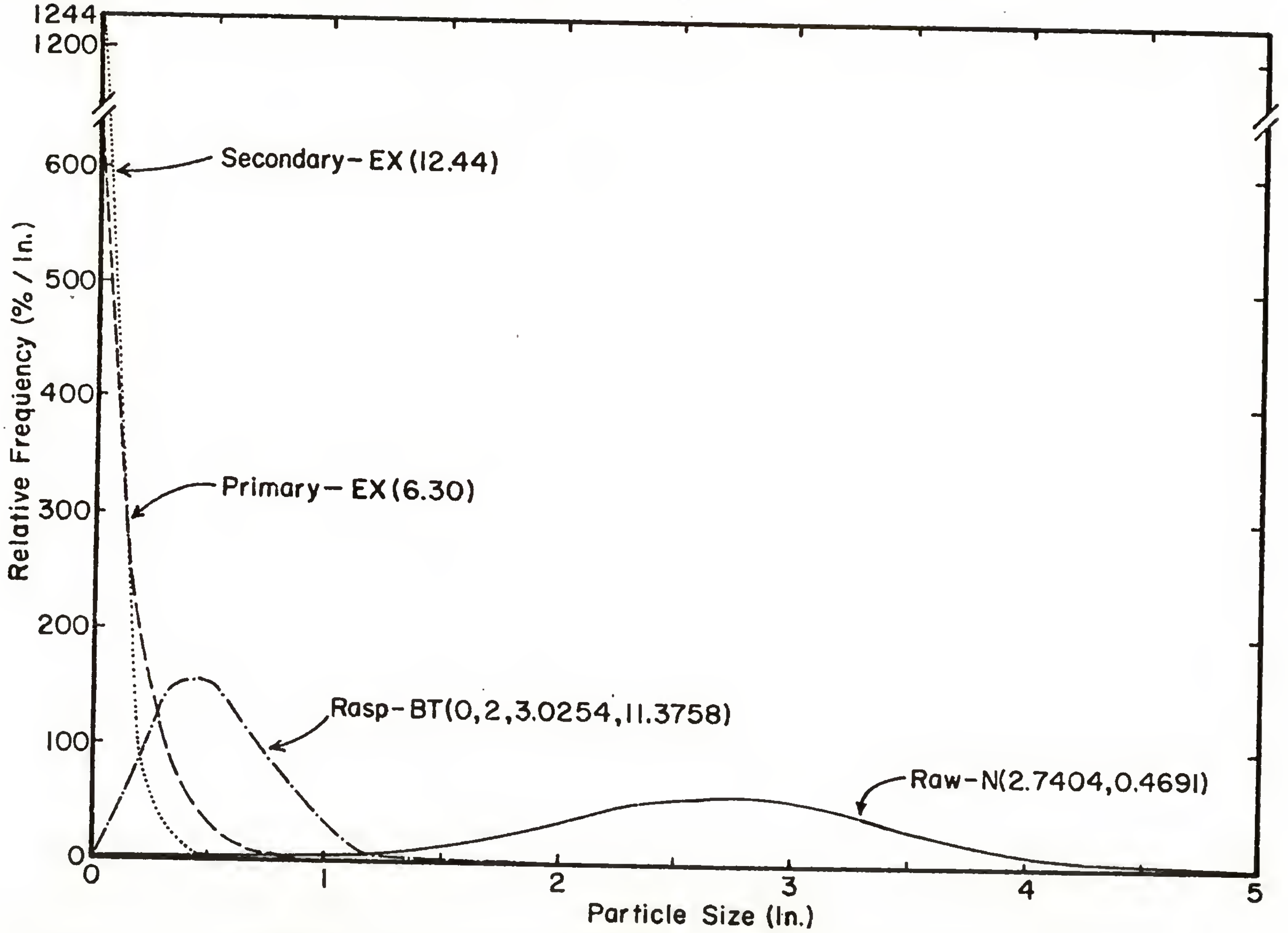


Figure I-10. Particle size distributions of glass waste from Gainesville, Florida, and Johnson City, Tennessee.

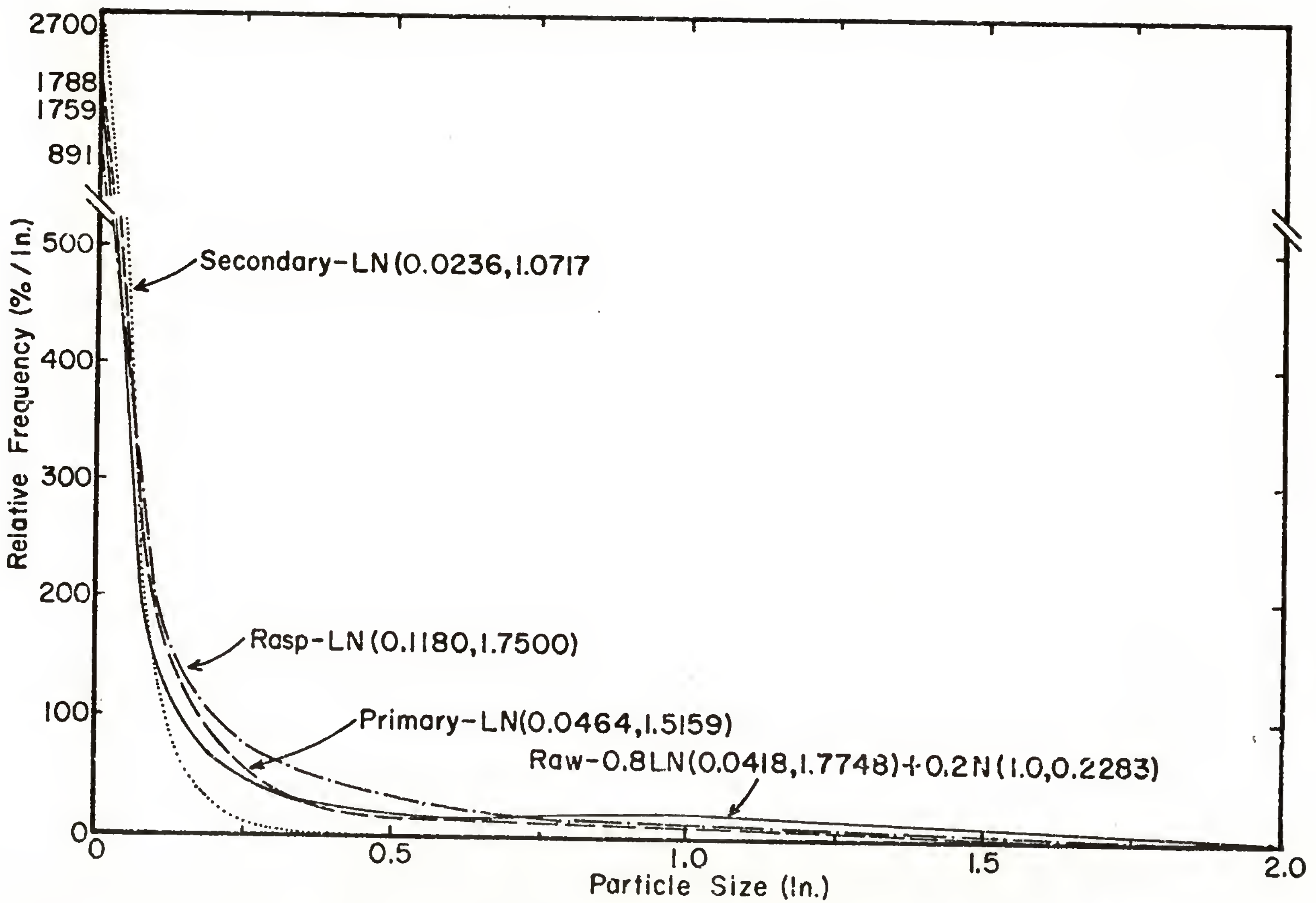


Figure I-11. Particle size distributions of sand and rock waste from Gainesville, Florida, and Johnson City, Tennessee.

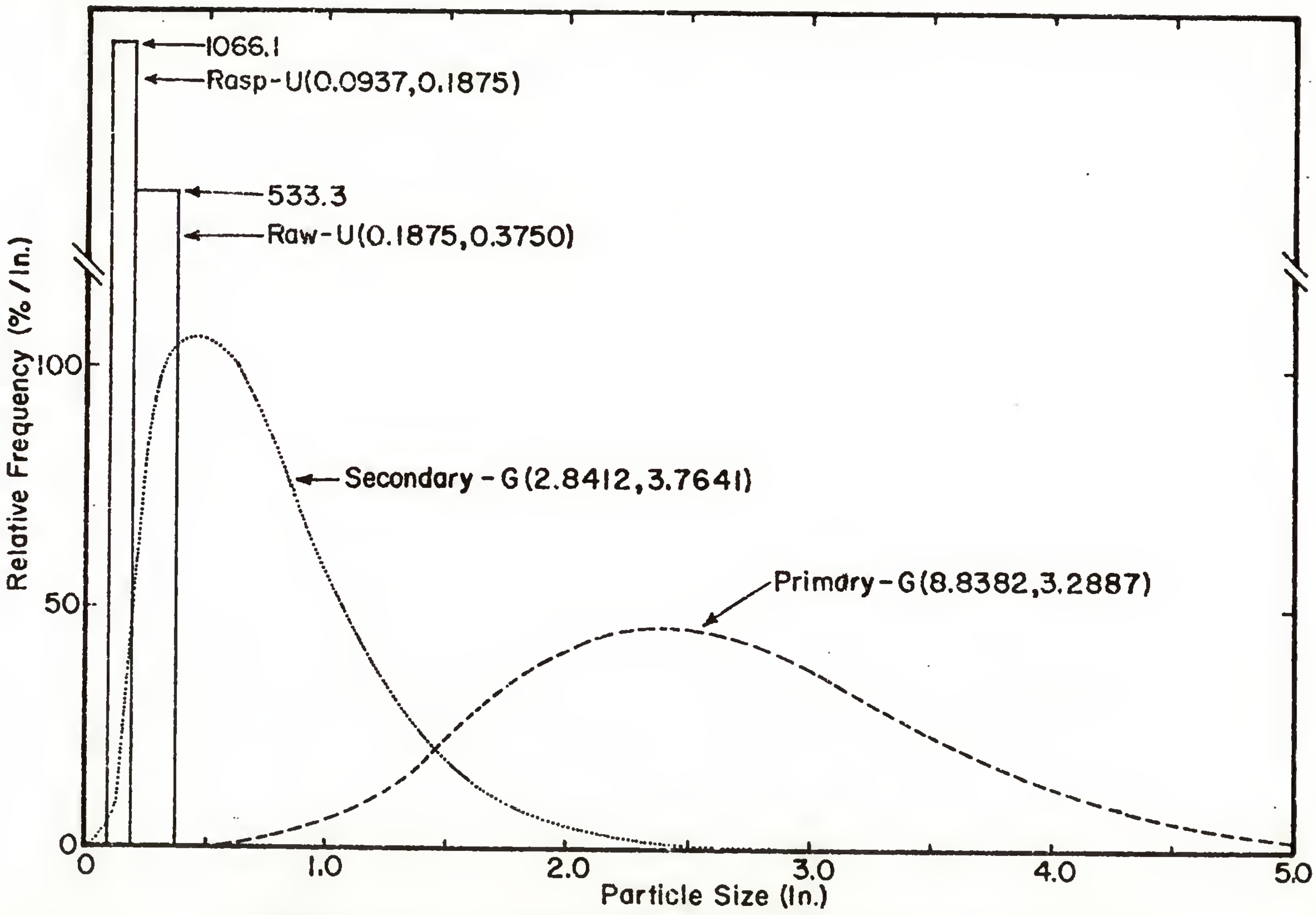


Figure I-12. Particle size distributions of miscellaneous waste from Gainesville, Florida, and Johnson City, Tennessee.

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John Adam Ruf was born January 16, 1939, in Kansas City, Missouri. He received both a Bachelor of Science in Civil Engineering (1962) and a Master of Science in Environmental Health Engineering (1966) from the University of Kansas.

After graduation in 1962, he was briefly employed as a Sanitary Engineer for Truman Schlup Consulting Engineers in Kansas City, Kansas. Then he was employed as a Sanitary Engineer with the Kansas State Department of Health at Topeka, Kansas. In 1966 he accepted an appointment as a Commissioned Officer with the U.S. Public Health Service, and was assigned as a project officer in the new federal solid waste program at Washington, D.C., and subsequently, Cincinnati, Ohio.

In September 1968, he was reassigned to Gainesville, Florida, as the federal representative on the federally funded compost plant, and also was allowed to study part-time for a doctoral degree at the Environmental Engineering Department, University of Florida. He assumed full academic status when the federal assistance to the compost plant terminated in 1970.

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Professor of Environmental
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